

# The role of nitrogen and phosphorus in promoting the occurrence of harmful algal blooms in marine and freshwater ecosystems



**Christopher J. Gobler**



**Stony Brook University**  
**School of Marine and**  
**Atmospheric Sciences**

# *Why have HABs expanded globally?*

- More comprehensive assessment, monitoring, and assessment.
  - Toxins
  - Broader definition
- Anthropogenic transport
- Climate change
- Anthropogenic nutrient loading

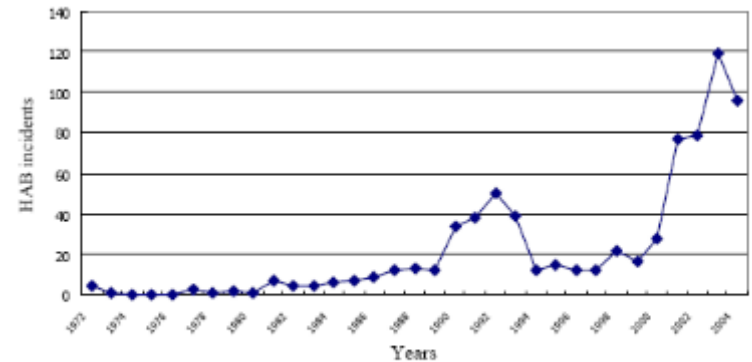
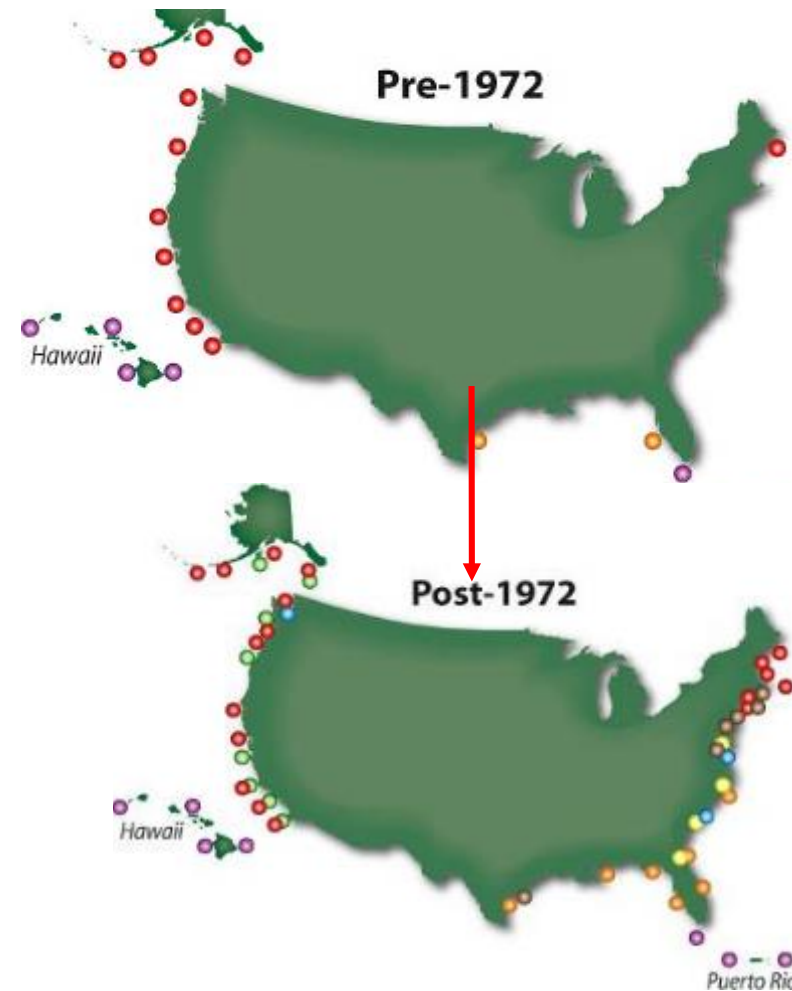
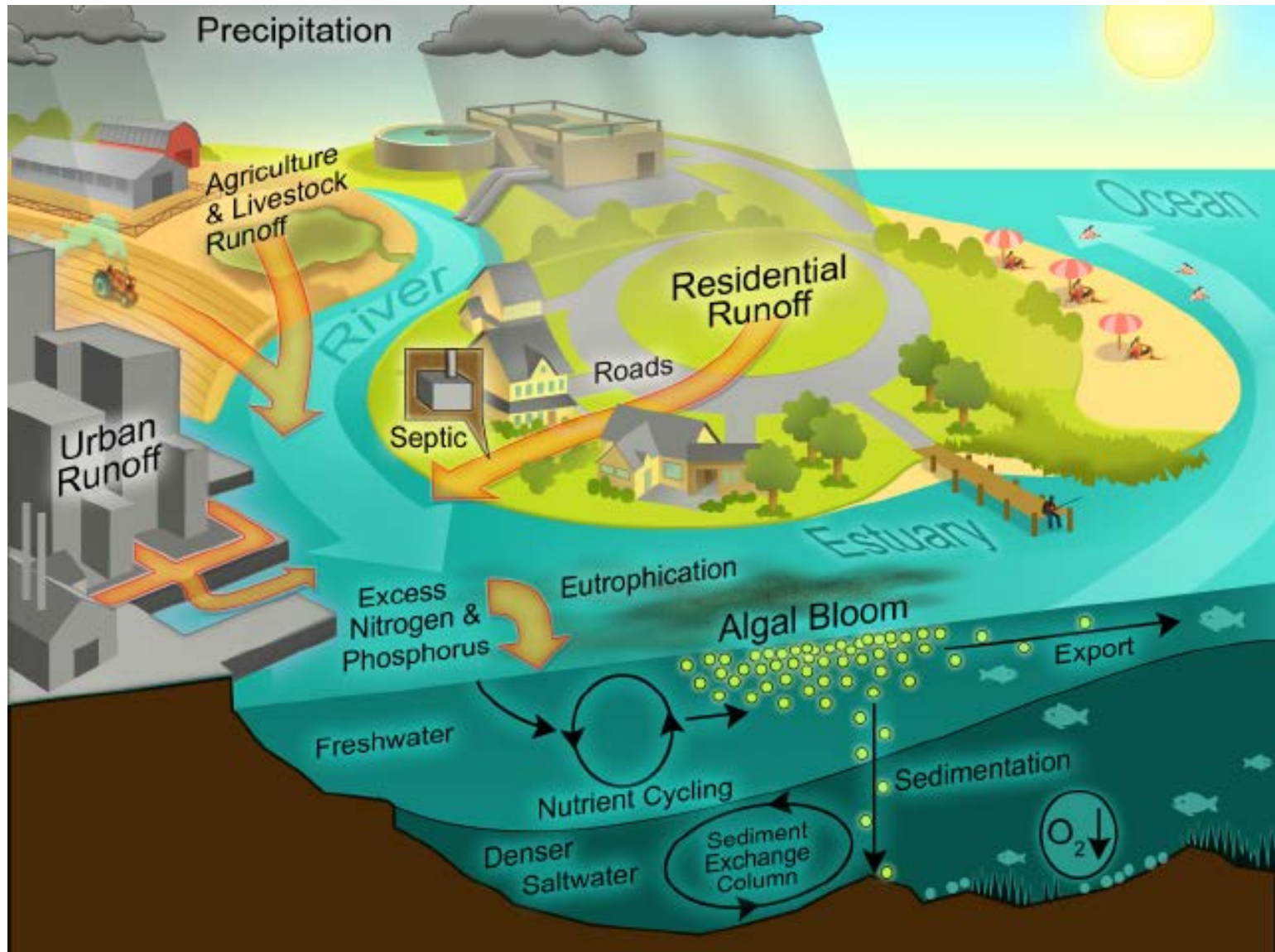


Figure 1 HAB incidents in coastal China from 1972 to 2004



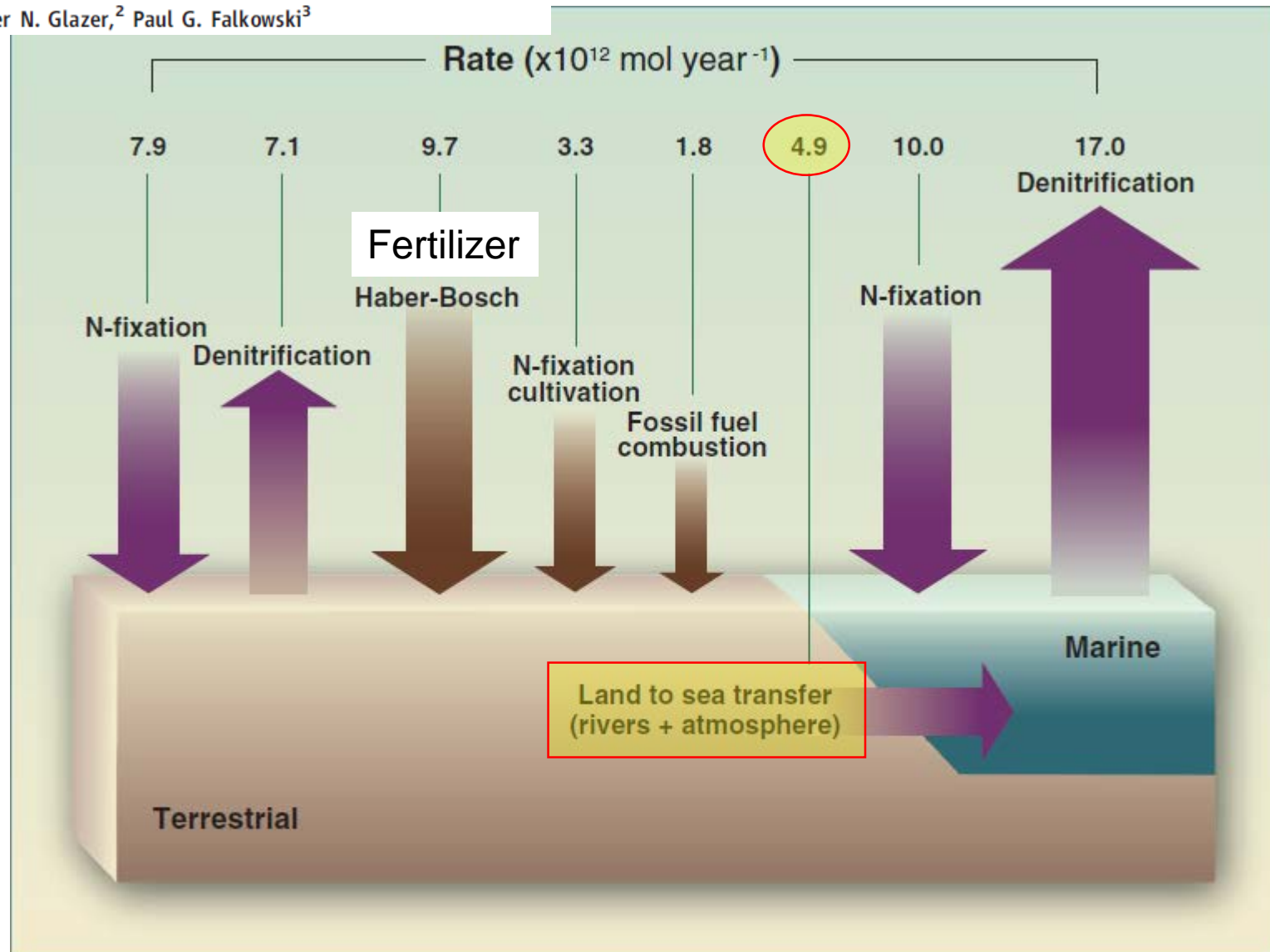
# Nutrient delivery processes



# The Evolution and Future of Earth's Nitrogen Cycle

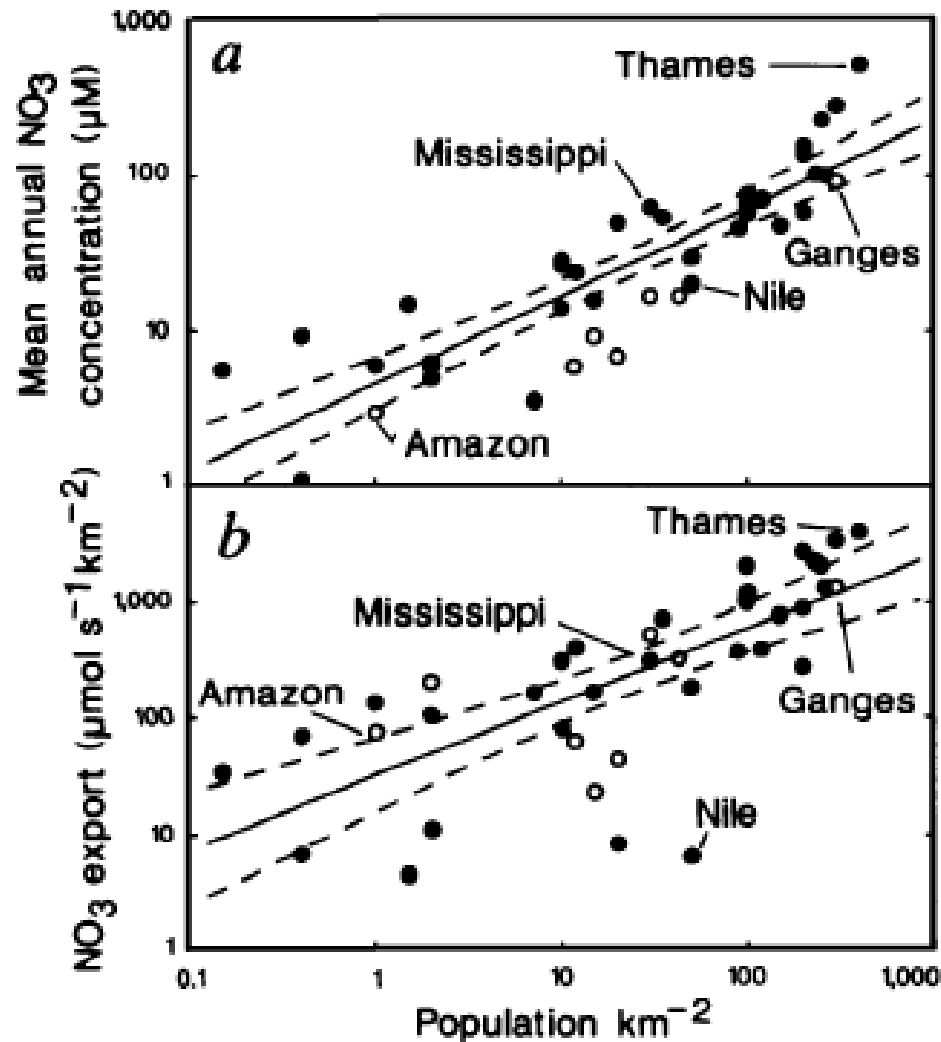
8 OCTOBER 2010 VOL 330 SCIENCE

Donald E. Canfield,<sup>1\*</sup> Alexander N. Glazer,<sup>2</sup> Paul G. Falkowski<sup>3</sup>



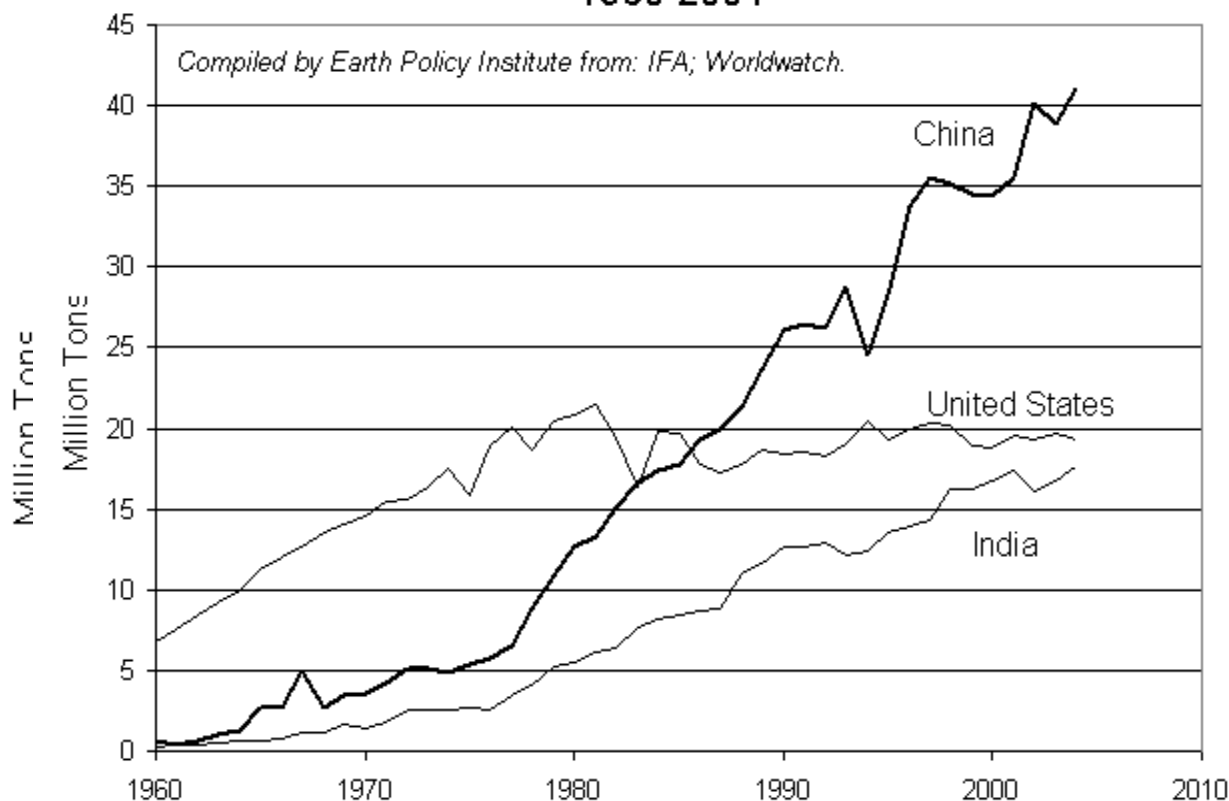
**Fig. 4.** Rates of nitrogen flux in the modern nitrogen cycle depend on the efficiency of the transformations between reservoirs. Arrow size reflects relative size of the flux. The dark brown arrows represent anthropogenic inputs (25, 45, 46, 52, 53, 68, 69).

Nitrate levels in rivers are related to watershed population density.



# ***Fertilizer is the largest source of nitrogen to coastal waters***

**Fertilizer Use in China, India, and the United States,  
1960-2004**



*Compiled by Earth Policy Institute from: IFA; Worldwatch.*

*Some HABs are directly  
caused by anthropogenic  
nutrient loading...*

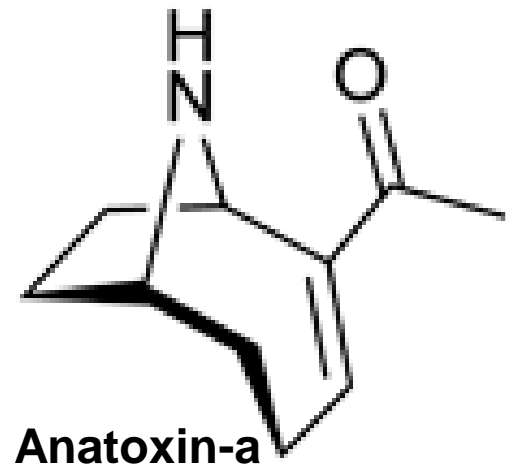
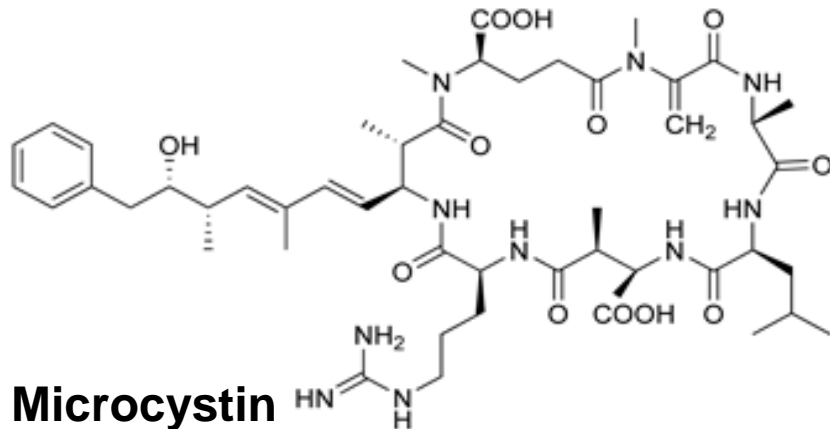
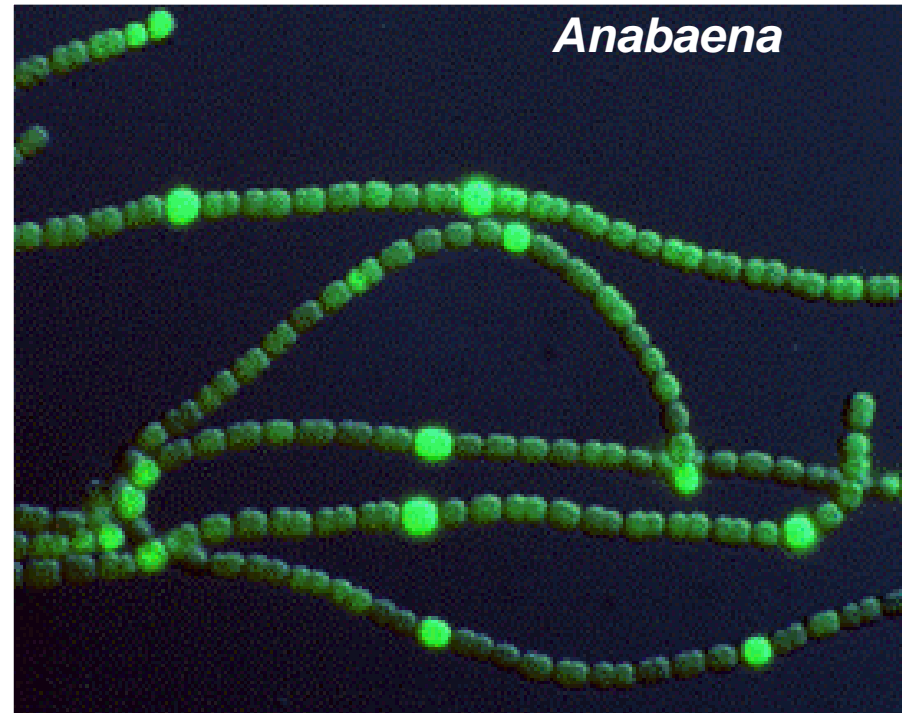
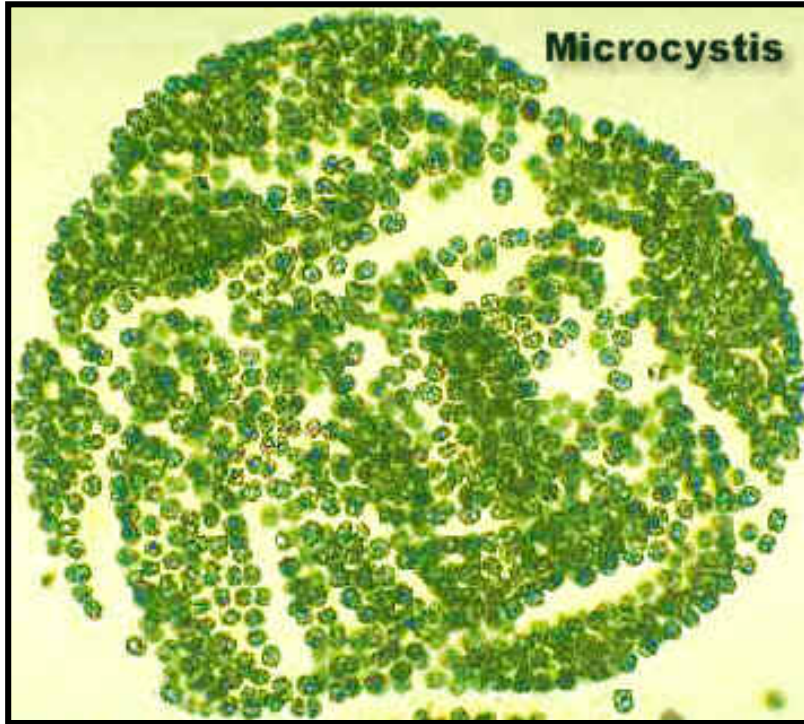


## Eutrophication and harmful algal blooms: A scientific consensus

J. Heisler<sup>a,3</sup>, P.M. Glibert<sup>b,\*</sup>, J.M. Burkholder<sup>c</sup>, D.M. Anderson<sup>d</sup>, W. Cochlan<sup>e</sup>, W.C. Dennison<sup>b</sup>,  
Q. Dortch<sup>f</sup>, C.J. Gobler<sup>g</sup>, C.A. Heil<sup>h,1</sup>, E. Humphries<sup>i</sup>, A. Lewitus<sup>j,k,2</sup>, R. Magnien<sup>l,2</sup>,  
H.G. Marshall<sup>m</sup>, K. Sellner<sup>n</sup>, D.A. Stockwell<sup>o</sup>, D.K. Stoecker<sup>b</sup>, M. Suddleson<sup>f</sup>

- (1) Degraded water quality from increased nutrient pollution promotes the development and persistence of many HABs and is one of the reasons for their expansion in the U.S. and other nations;
- (2) The composition—not just the total quantity—of the nutrient pool impacts HABs;
- (3) High-biomass blooms must have exogenous nutrients to be sustained;
- (4) Both chronic and episodic nutrient delivery promote HAB development;
- (5) Recently developed tools and techniques are already improving the detection of some HABs, and emerging technologies are rapidly advancing toward operational status for the prediction of HABs and their toxins;
- (6) Experimental studies are critical to further the understanding about the role of nutrients in HABs expression, and will strengthen prediction and mitigation of HABs; and
- (7) Management of nutrient inputs to the watershed can lead to significant reduction in HABs.

# Freshwater cyanobacteria and their toxins

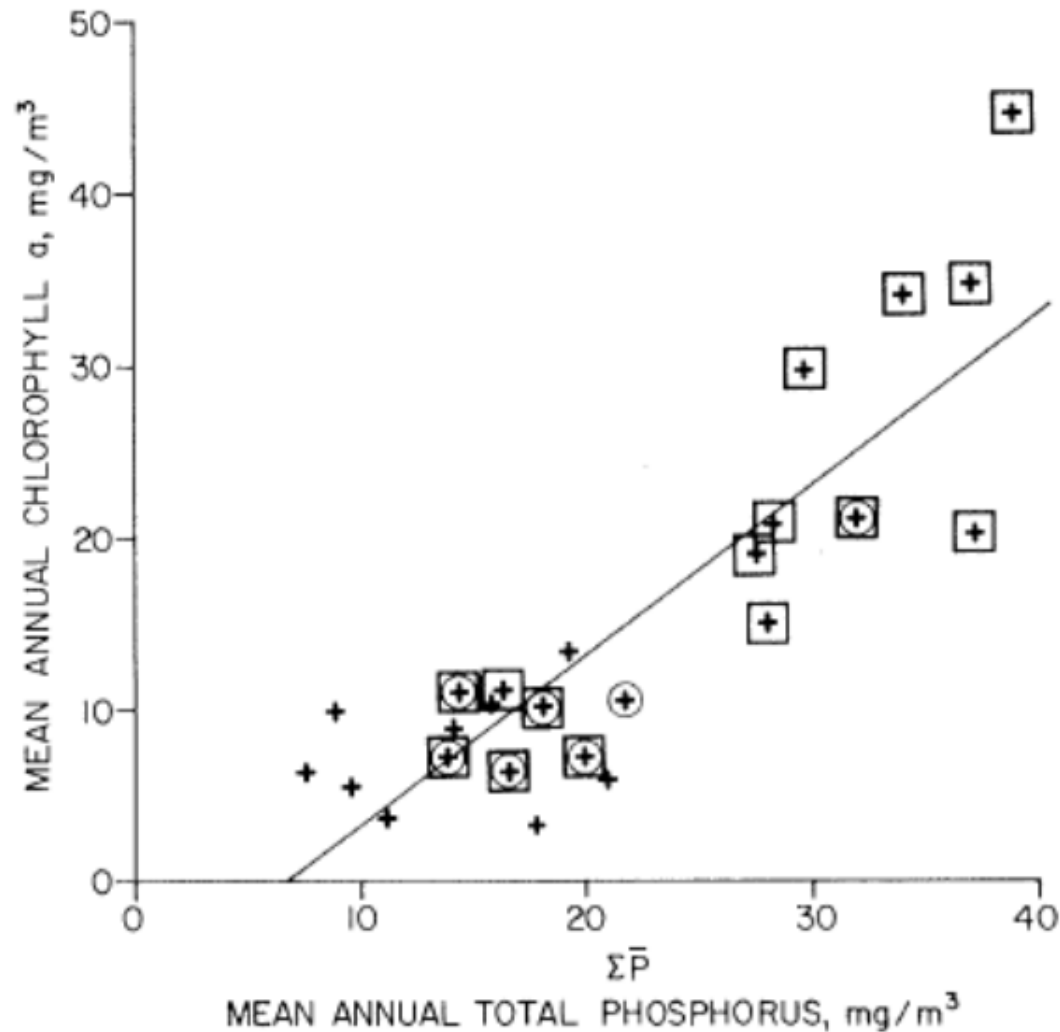


# Freshwater cyanobacteria and nutrients

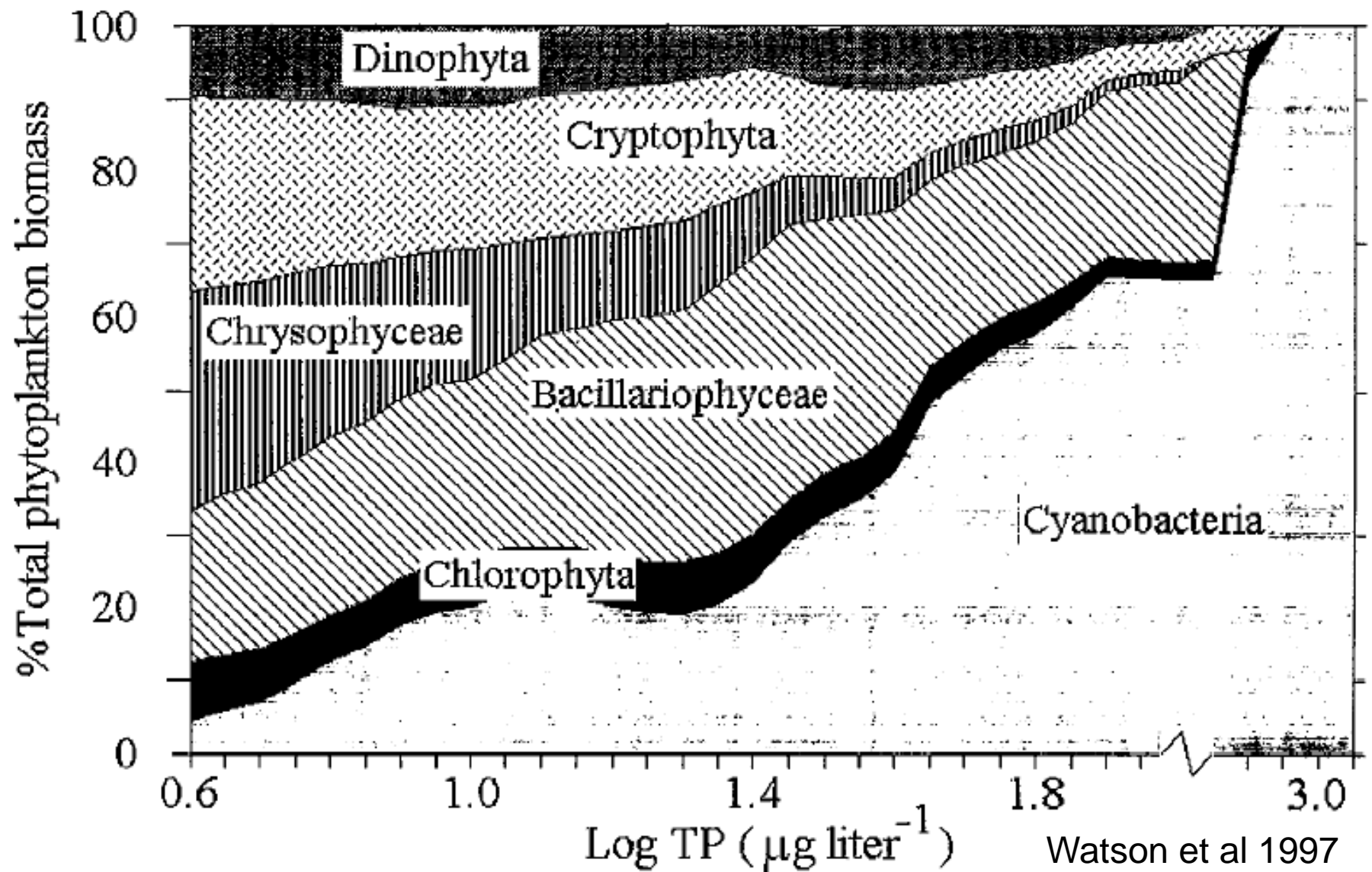
- As bodies of freshwater become enriched in nutrients, the relative abundance of cyanobacteria within phytoplankton community increases (Fogg, 1969; Renoylds & Walsby, 1975; Smith, 1986; Trimbee & Prepas, 1987; Renolds, 1987; Paerl, 1988b; Paerl, 1997; Watson et al., 1997; Paerl & Huisman, 2008).
- Summer phytoplankton communities are dominated by cyanobacteria at total phosphorus concentrations  $>100 \mu\text{g P L}^{-1}$  (Trimbee & Prepas, 1987; Jensen et al., 1994; Watson et al., 1997; Downing et al., 2001).

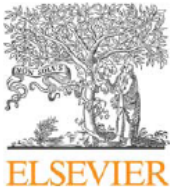


# Chlorophyll *a* and P in Canadian lakes



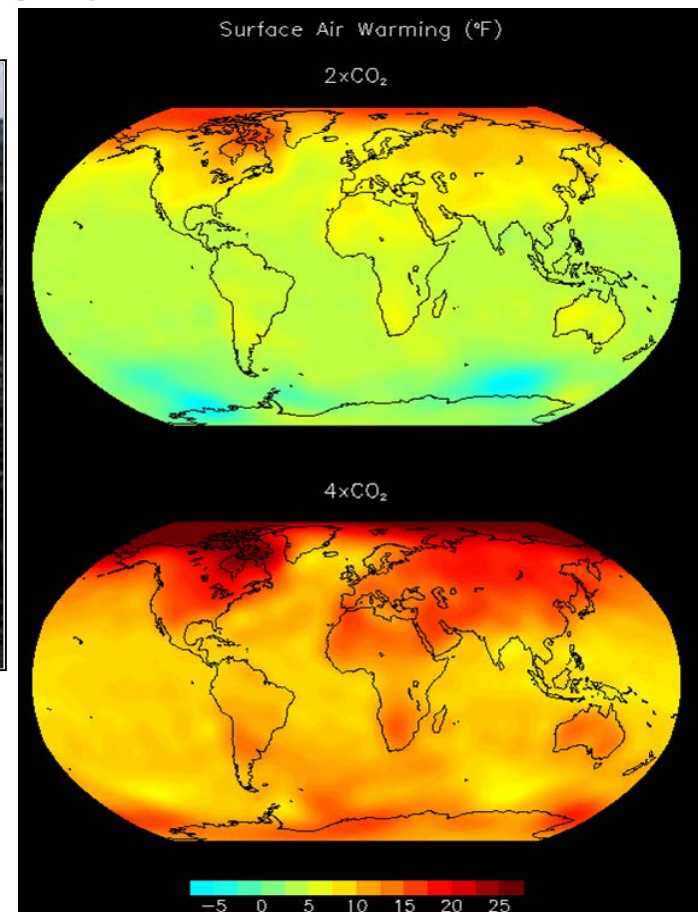
# Phosphorus and freshwater cyanobacteria



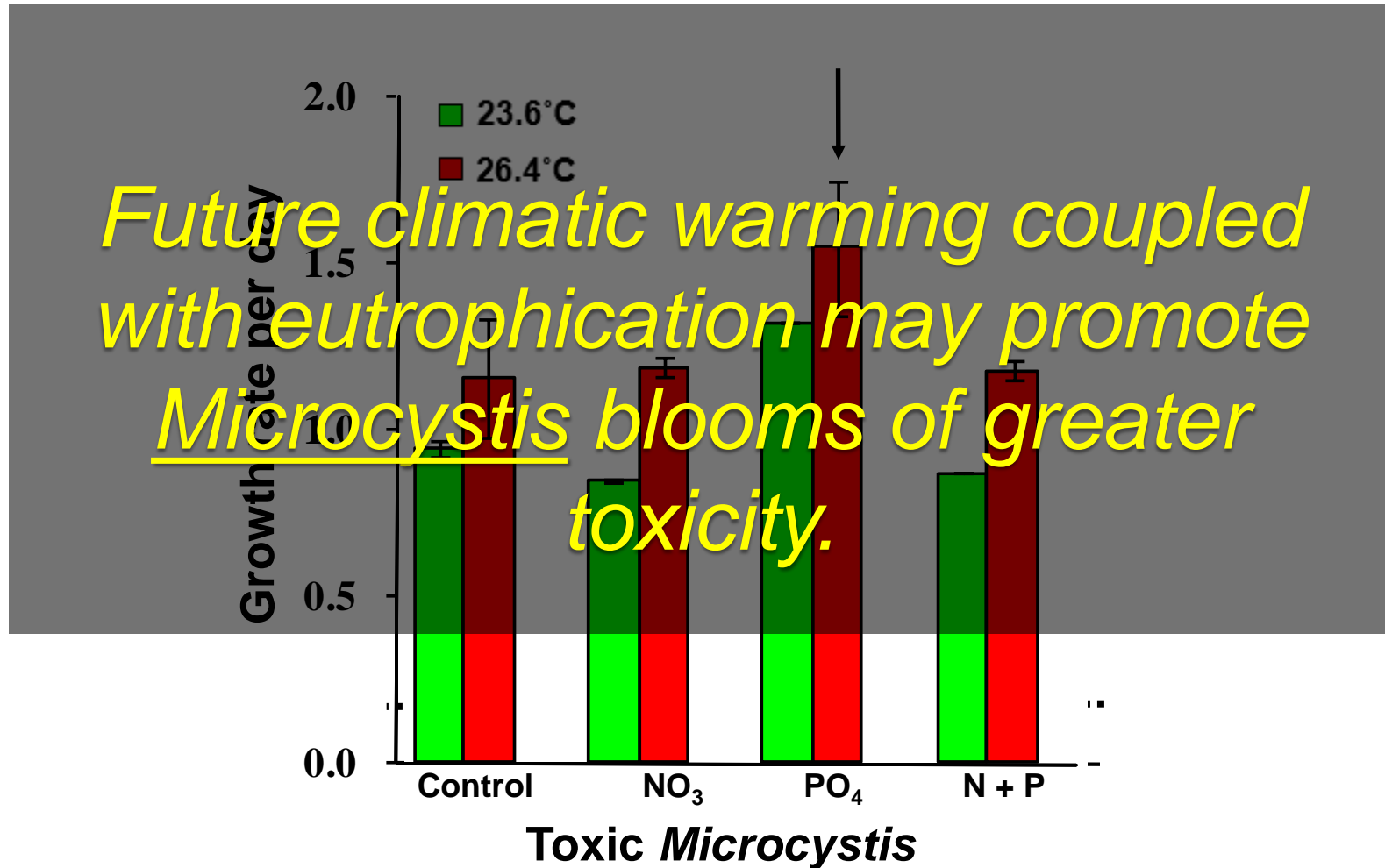


## The effects of temperature and nutrients on the growth and dynamics of toxic and non-toxic strains of *Microcystis* during cyanobacteria blooms

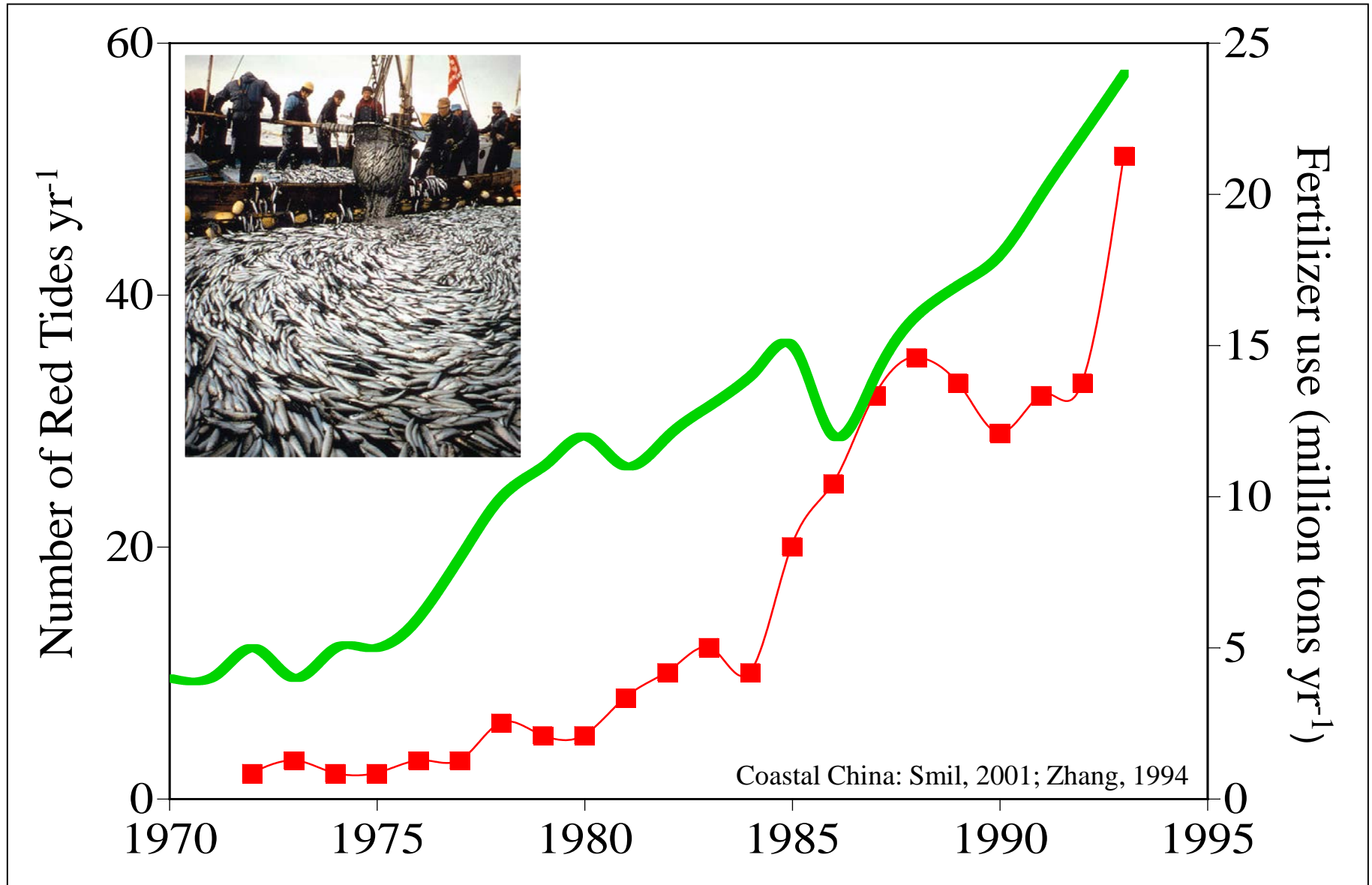
Timothy W. Davis<sup>a</sup>, Dianna L. Berry<sup>a</sup>, Gregory L. Boyer<sup>b</sup>, Christopher J. Gobler<sup>a,\*</sup>



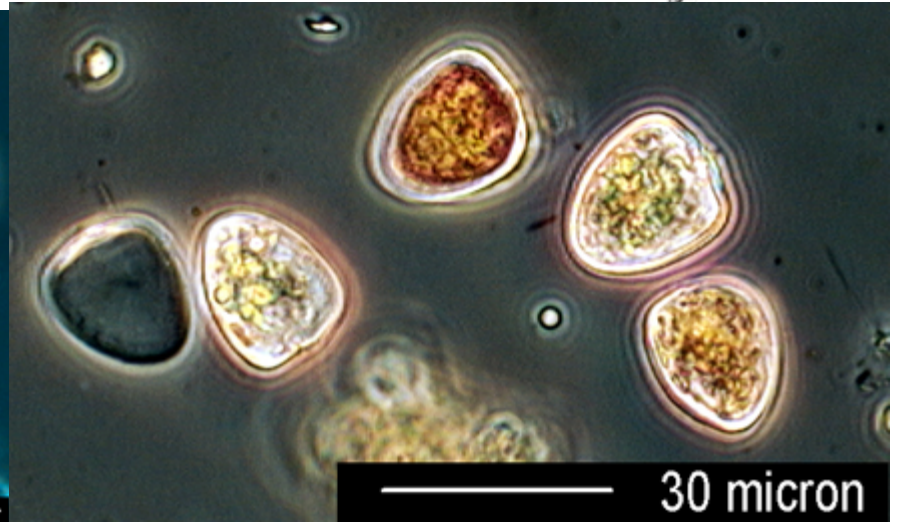
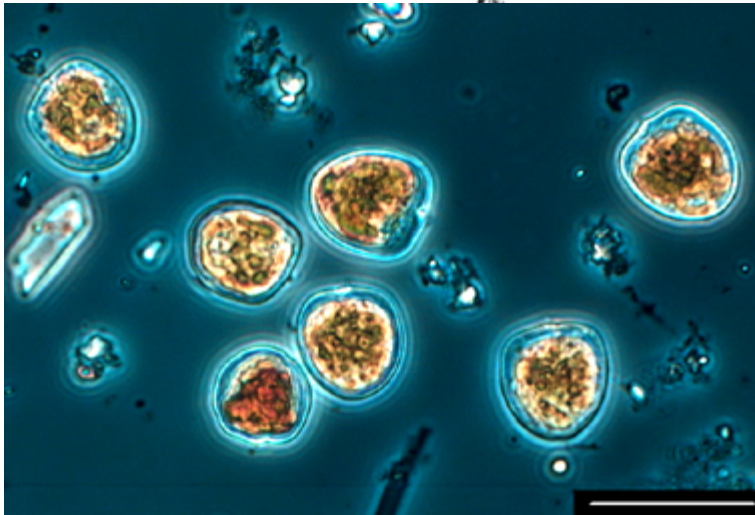
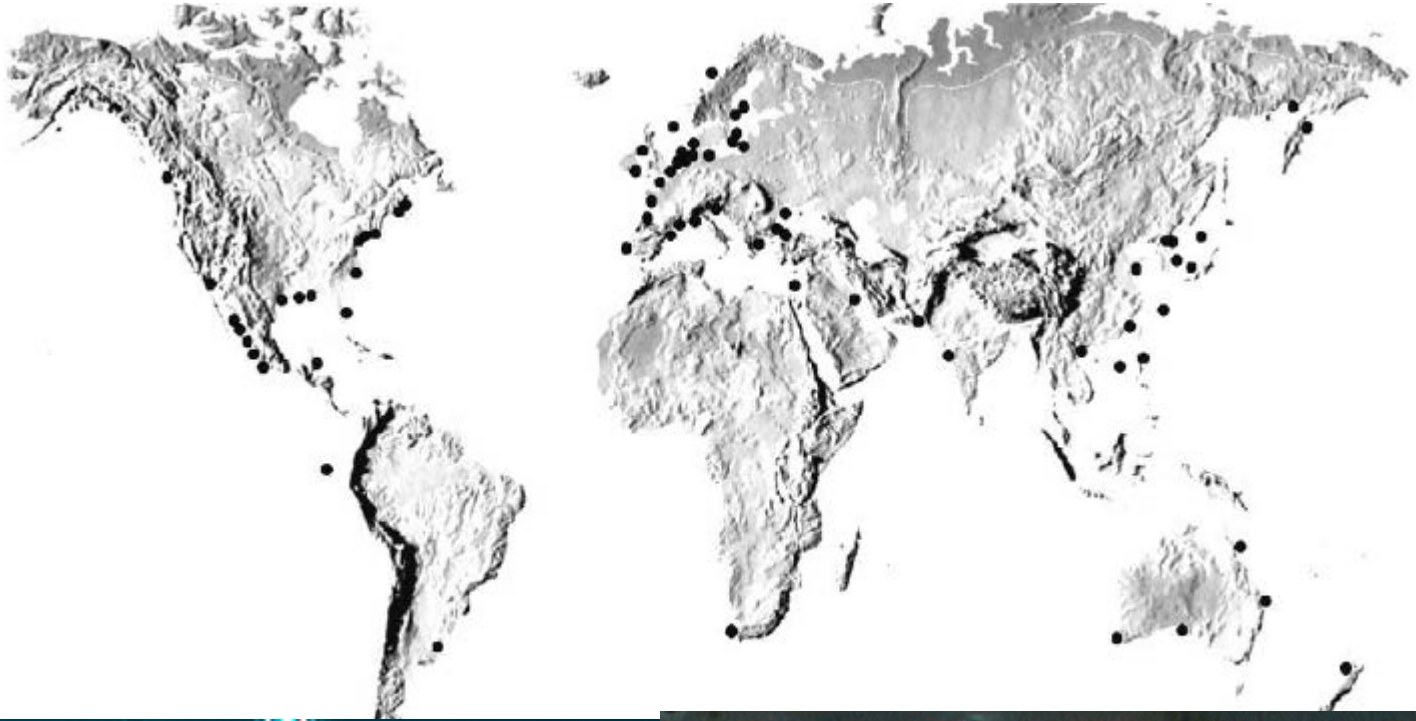
# Interaction between temperature and anthropogenic nutrient loading



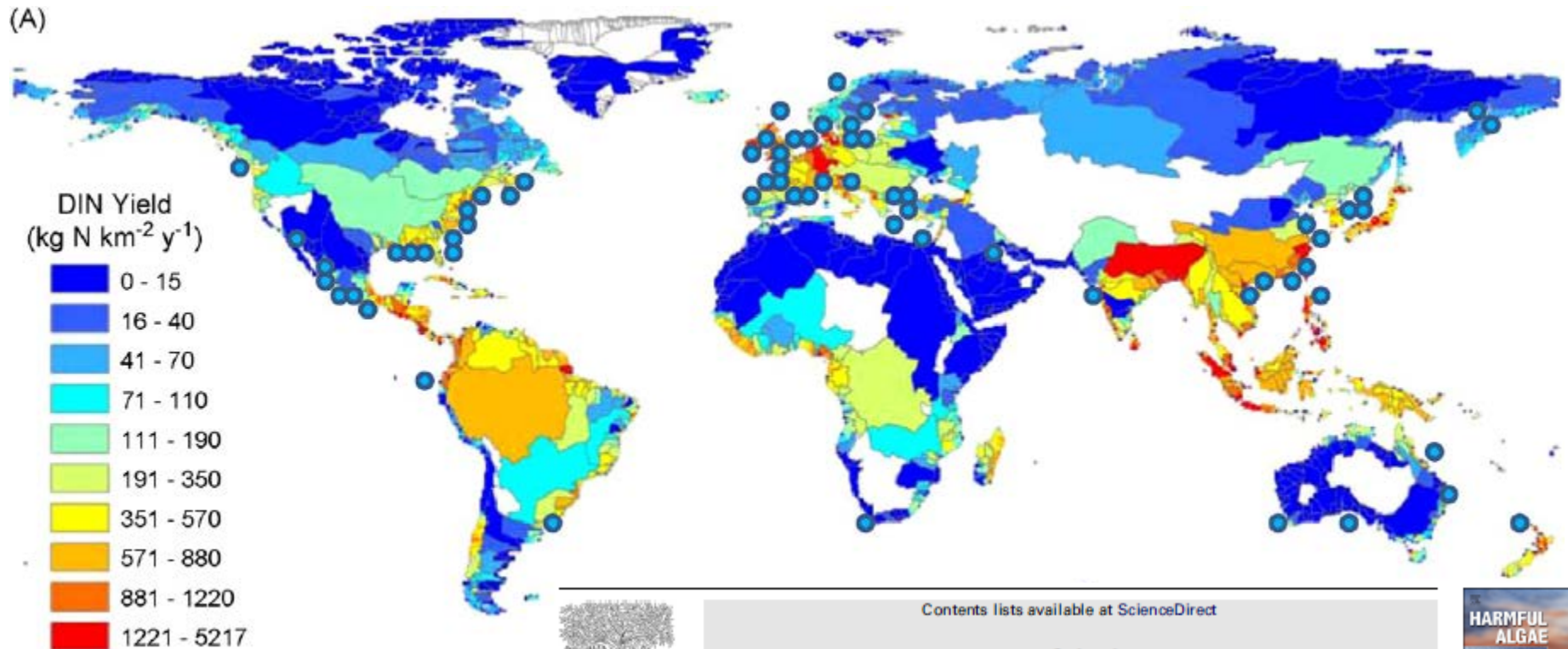
# Nutrient loading and HABs in China:



# *Prorocentrum minimum* blooms



# *Prorocentrum minimum* and nitrogen



ELSEVIER

Contents lists available at ScienceDirect

Harmful Algae

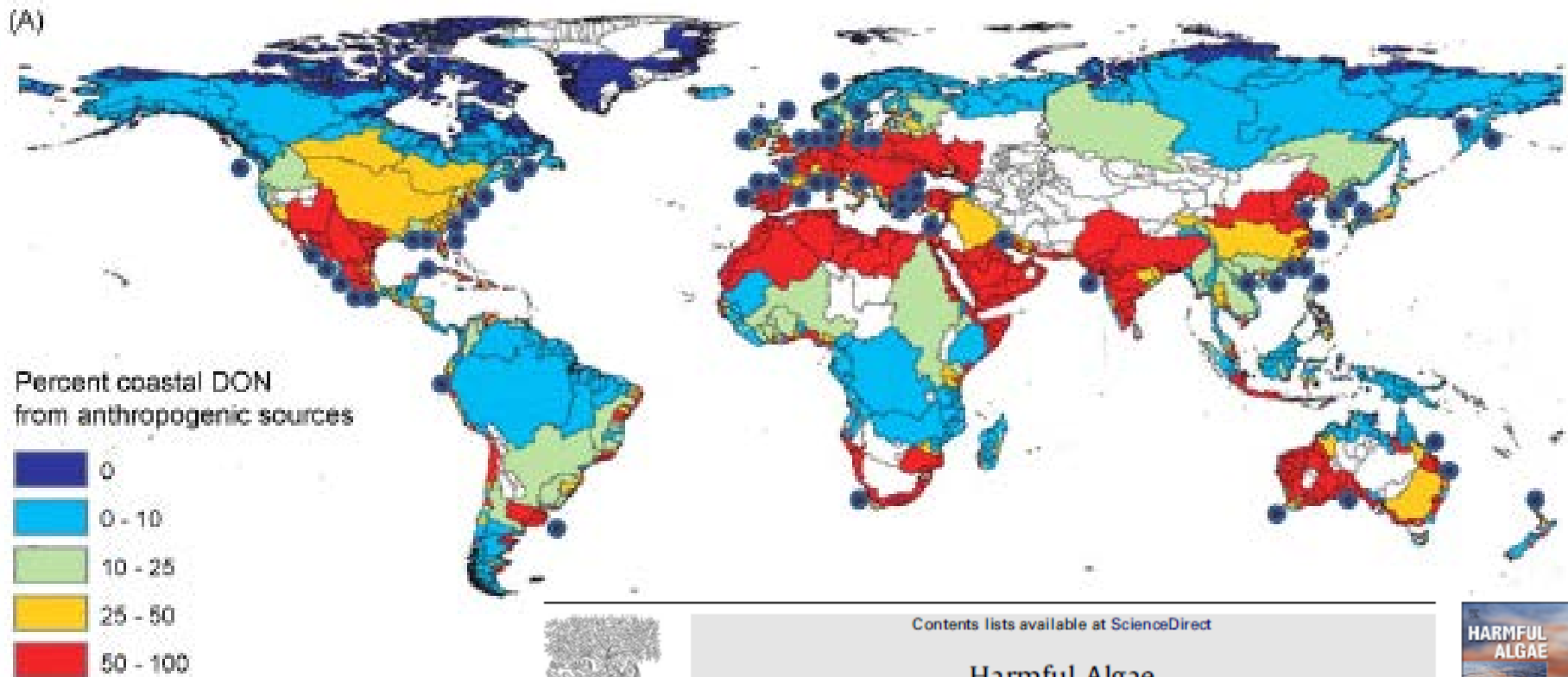
journal homepage: [www.elsevier.com/locate/hal](http://www.elsevier.com/locate/hal)



*Prorocentrum minimum* tracks anthropogenic nitrogen and phosphorus inputs on a global basis: Application of spatially explicit nutrient export models

Patricia M. Glibert<sup>a,\*</sup>, Emilio Mayorga<sup>b</sup>, Sybil Seitzinger<sup>b</sup>

# *Prorocentrum minimum* and anthropogenic DON



Contents lists available at ScienceDirect

Harmful Algae

journal homepage: [www.elsevier.com/locate/hal](http://www.elsevier.com/locate/hal)



*Prorocentrum minimum* tracks anthropogenic nitrogen and phosphorus inputs on a global basis: Application of spatially explicit nutrient export models

Patricia M. Glibert<sup>a,\*</sup>, Emilio Mayorga<sup>b</sup>, Sybil Seitzinger<sup>b</sup>



Contents lists available at SciVerse ScienceDirect

## Estuarine, Coastal and Shelf Science

journal homepage: [www.elsevier.com/locate/ecss](http://www.elsevier.com/locate/ecss)



### Review

## Harmful algal blooms: How strong is the evidence that nutrient ratios and forms influence their occurrence?

Keith Davidson<sup>a,\*</sup>, Richard J. Gowen<sup>b</sup>, Paul Tett<sup>a</sup>, Eileen Bresnan<sup>c</sup>, Paul J. Harrison<sup>d</sup>, April McKinney<sup>b</sup>, Stephen Milligan<sup>e</sup>, David K. Mills<sup>e</sup>, Joe Silke<sup>f</sup>, Anne-Marie Crooks<sup>b</sup>

*Journal of Environmental Management* 146 (2014) 206–216



Contents lists available at ScienceDirect

## Journal of Environmental Management

journal homepage: [www.elsevier.com/locate/jenvman](http://www.elsevier.com/locate/jenvman)



## Anthropogenic nutrients and harmful algae in coastal waters

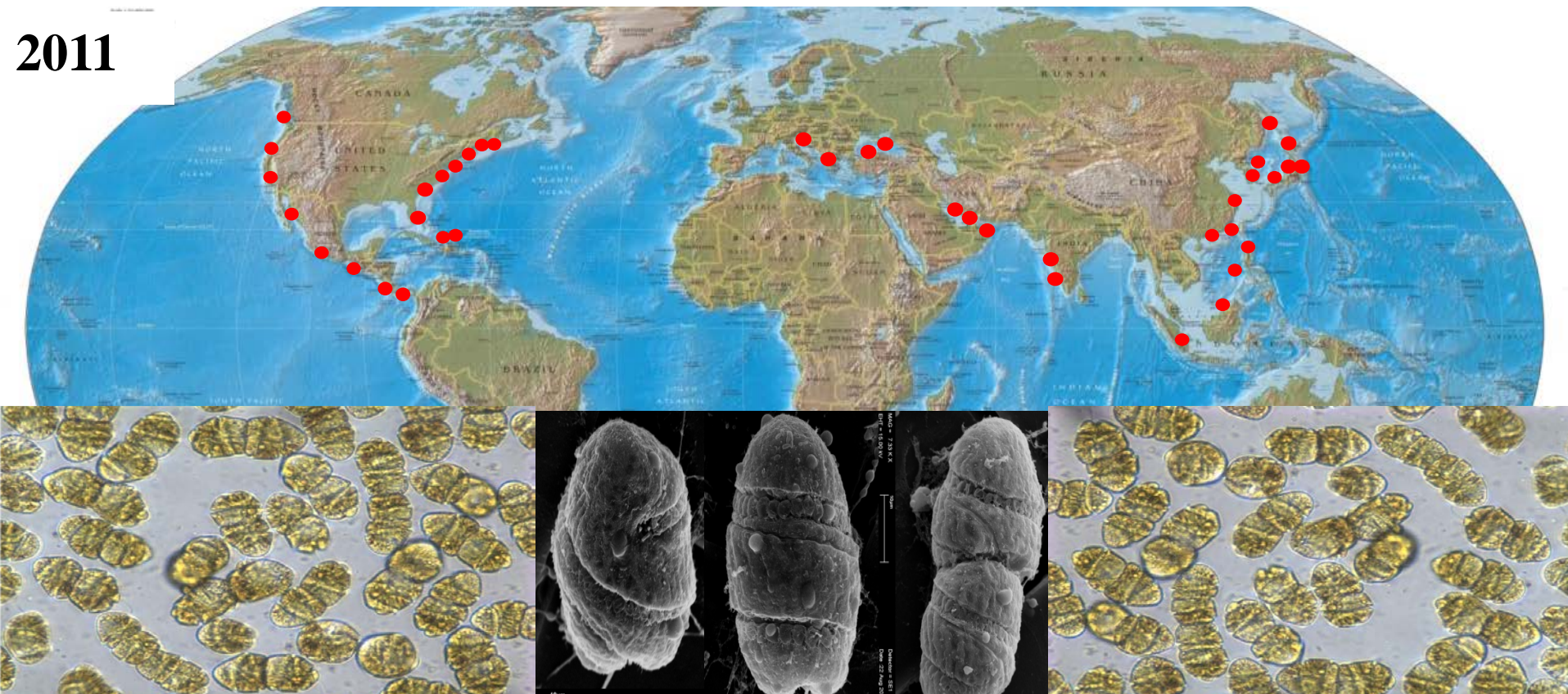
Keith Davidson<sup>a,\*</sup>, Richard J. Gowen<sup>b</sup>, Paul J. Harrison<sup>c</sup>, Lora E. Fleming<sup>d,e</sup>, Porter Hoagland<sup>f</sup>, Grigorios Moschonas<sup>a</sup>



*Some HABs display flexible  
nutritional ecology...*

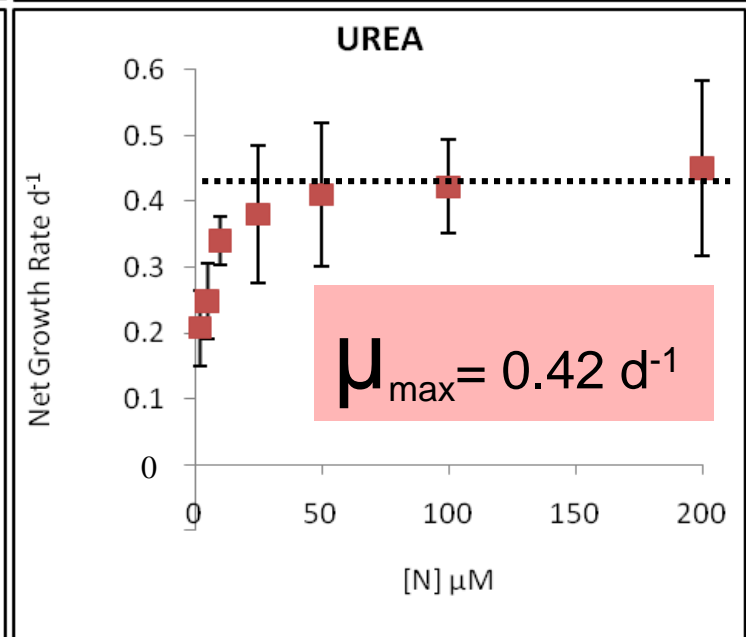
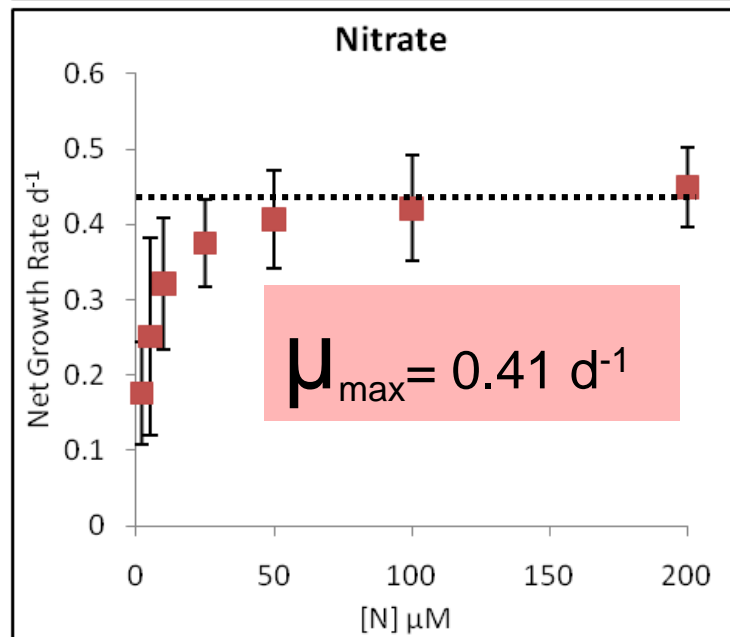
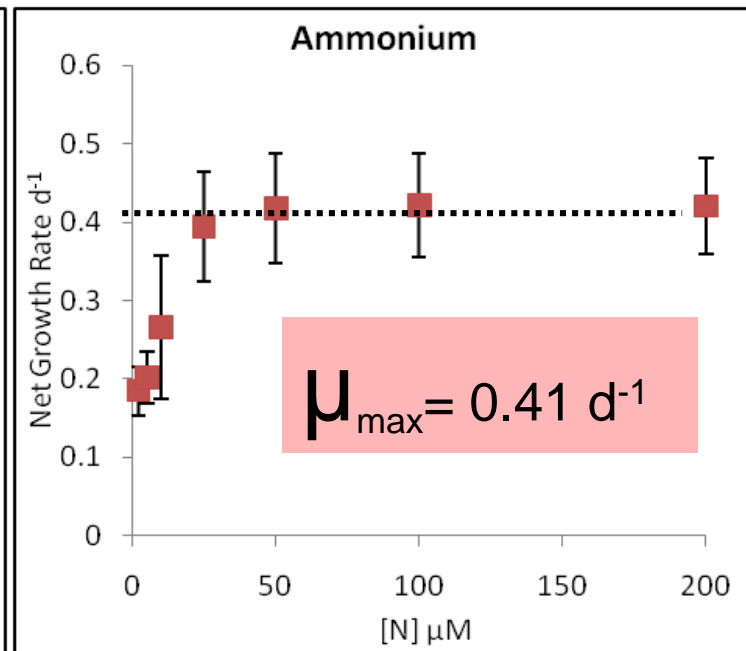
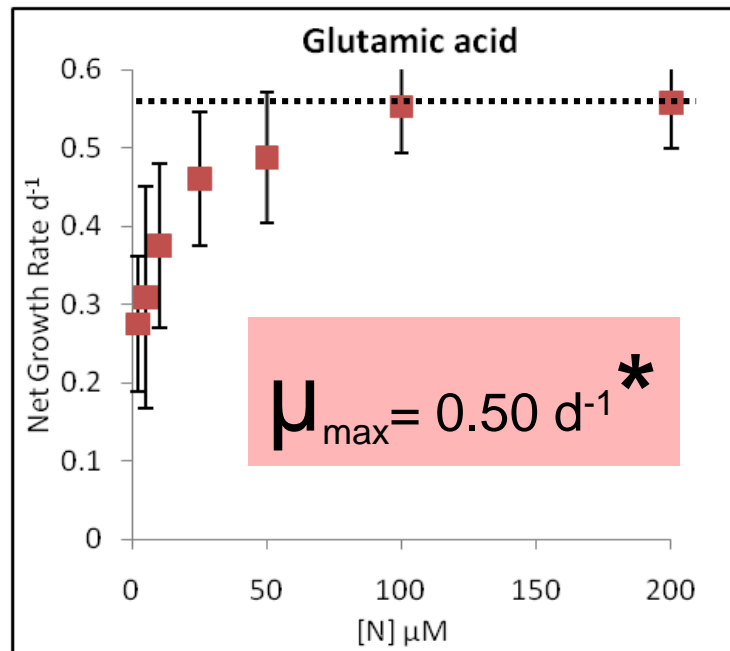
# Distribution of *Cochlodinium polykrikoides* blooms

- Highly toxic to many forms of marine life
- *Cochlodinium* blooms have spread across the Northern Hemisphere in the past decade: Korea, Japan, China, Malaysia, Philippines, Indonesia, India, Spain, Italy, Canada, Arabian Gulf, Mexico, Guatemala, Costa Rica, Puerto Rico, North America.





# *Cochlodinium* grows well on many N sources but quickest on DON



# Sampling sites

***Tributaries (high DIN) vs.  
open water sites (low DIN)***



**MEETING HOUSE  
CREEK**

**GREAT  
PECONIC BAY**

**OLD FORT  
POND**

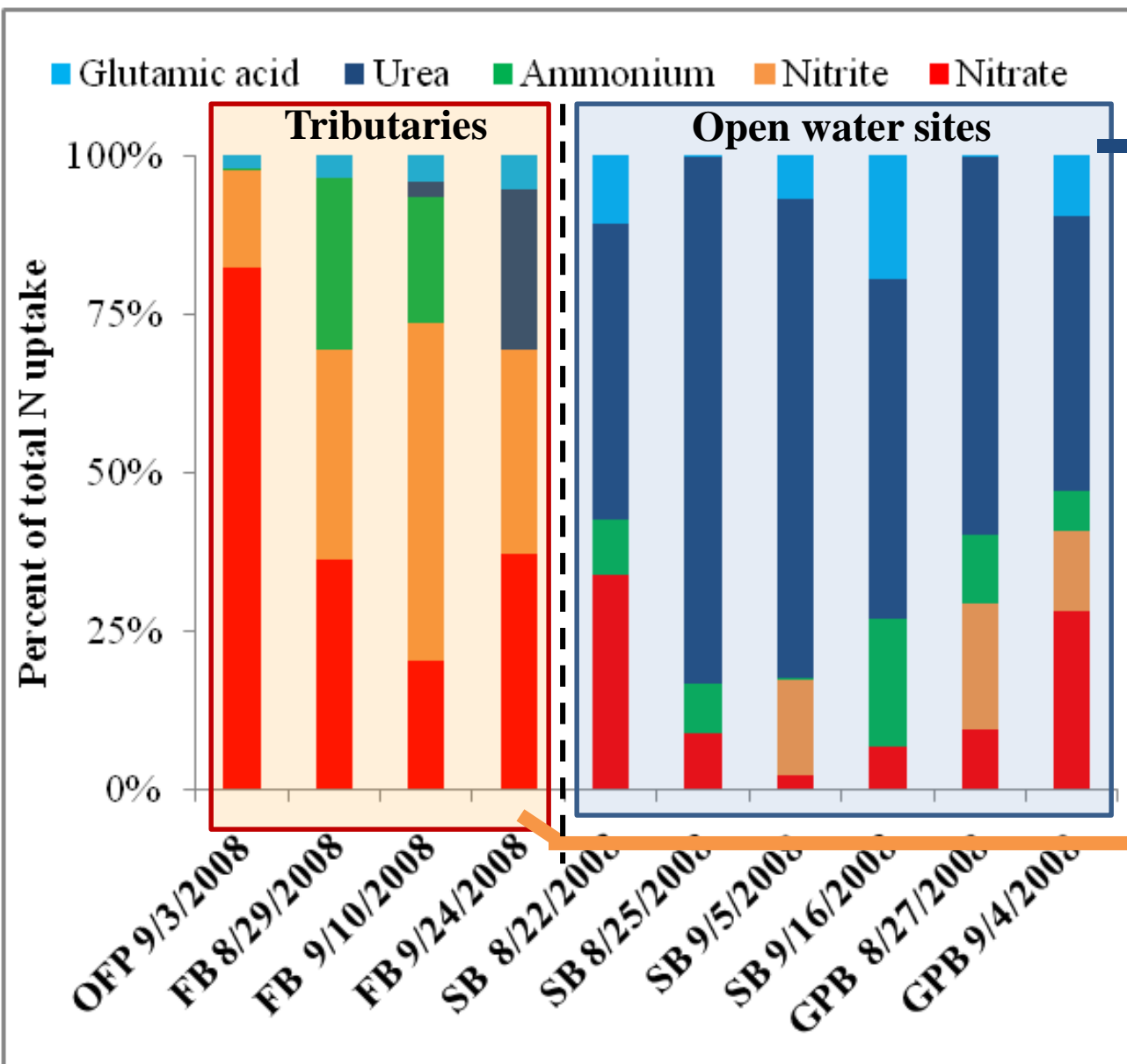
**FLANDERS  
BAY**

**SHINNECOCK  
BAY**





# N uptake, > 20 $\mu\text{m}$



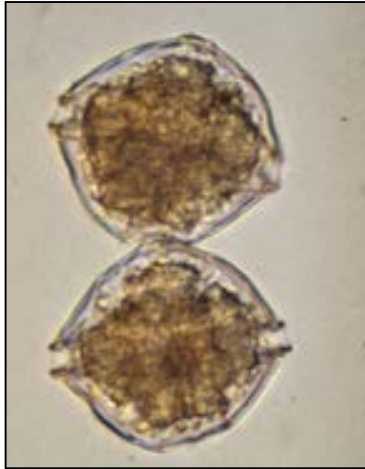
**Open water sites:**  
DON dominated uptake; Low [DIN]

*Cp was 70 - 98% of cells > 20  $\mu\text{m}$  for all ten experiments.*

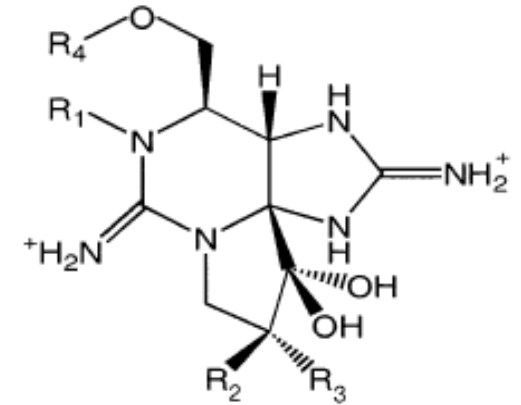
**Tributaries:**  
Mostly  $\text{NO}_3^-$ ,  $\text{NO}_2^-$  uptake; shallow sites with high  $[\text{NO}_3^-]$

*The interactions between  
nutrients and some HABs are  
ecosystem dependent.*

# *Alexandrium* red tides and paralytic shellfish poisoning (PSP)



*Alexandrium*



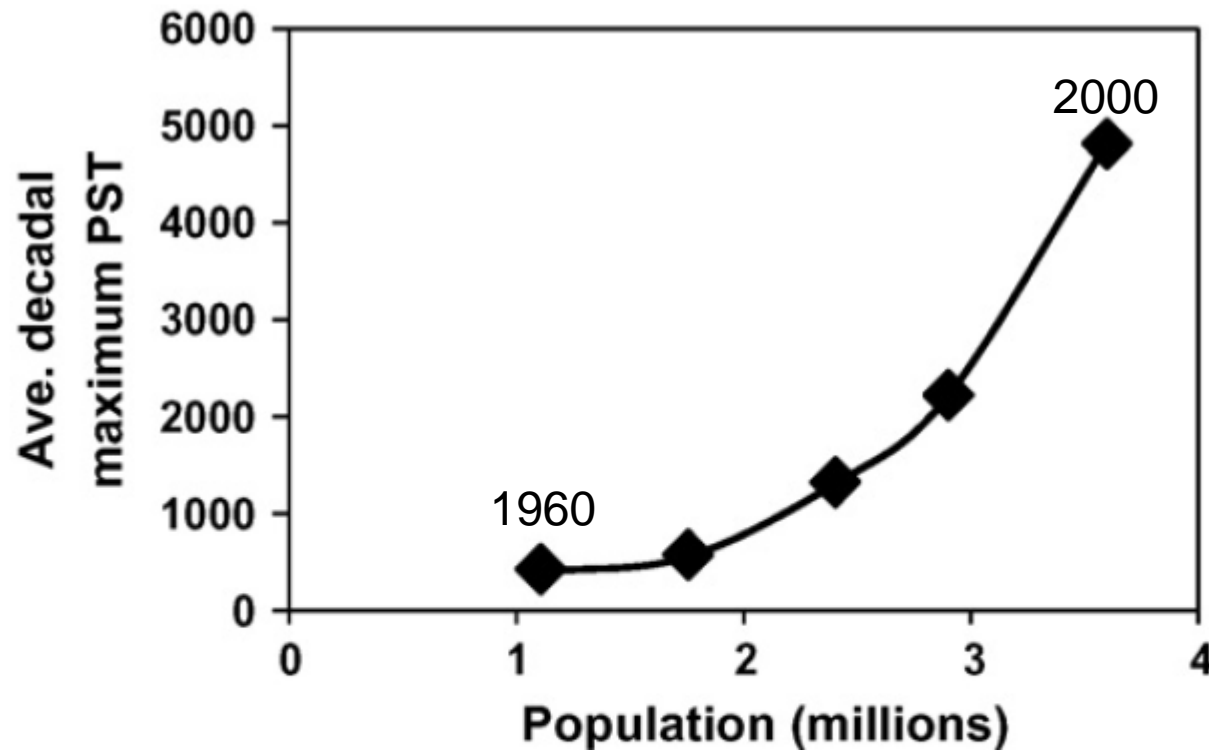
Saxitoxin



# Puget Sound, northwest USA, *Alexandrium* blooms and PSP



# *Alexandrium* in the Puget Sound

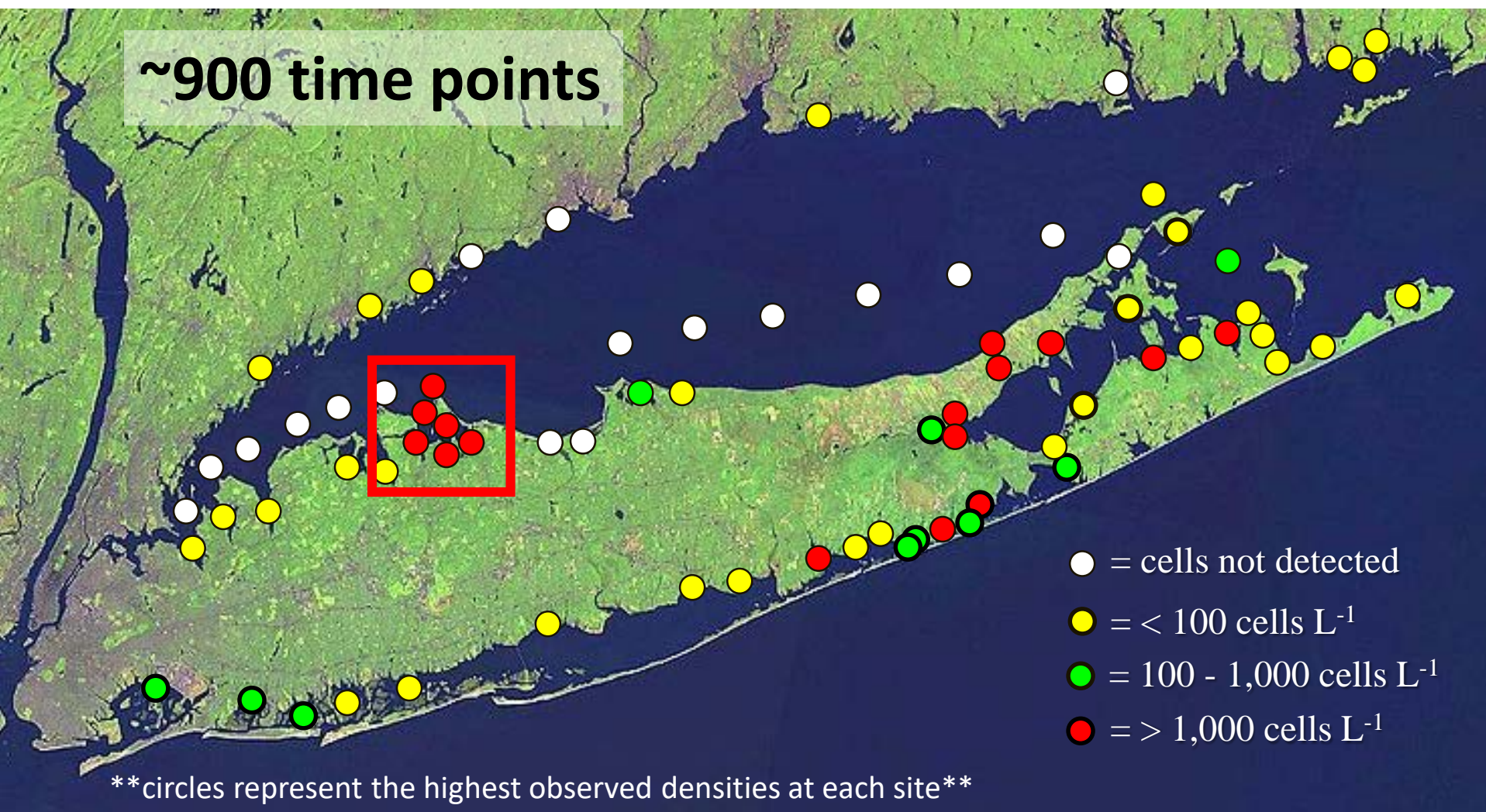


**Fig. 2.** Relationship between the growth in human population and the average decadal maximum paralytic shellfish toxins (PST) from dinoflagellate HABs from Puget Sound, Washington State, where continuous monitoring of paralytic shellfish poisoning has been ongoing since the mid-1950s. Human population data for the counties bordering Puget Sound for the past 40 years were derived from the U.S. census (redrawn from [Trainer et al., 2003](#)).

# *Alexandrium* blooms in New York, USA



# Presence of PSP-producing *Alexandrium* in LI and CT: 2007-2017

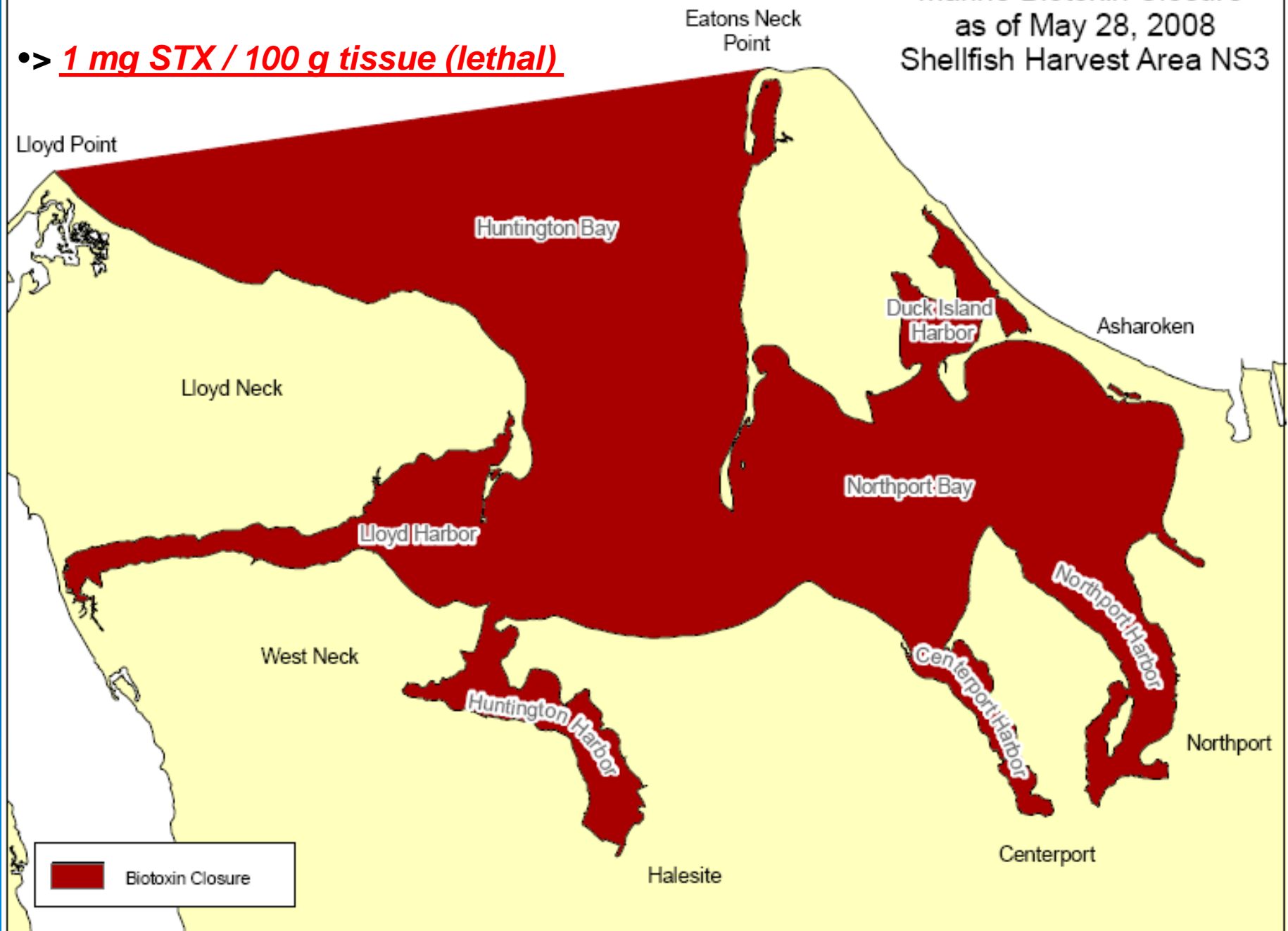


- *Alexandrium* found at 49 of 65 sites sampled (75%)

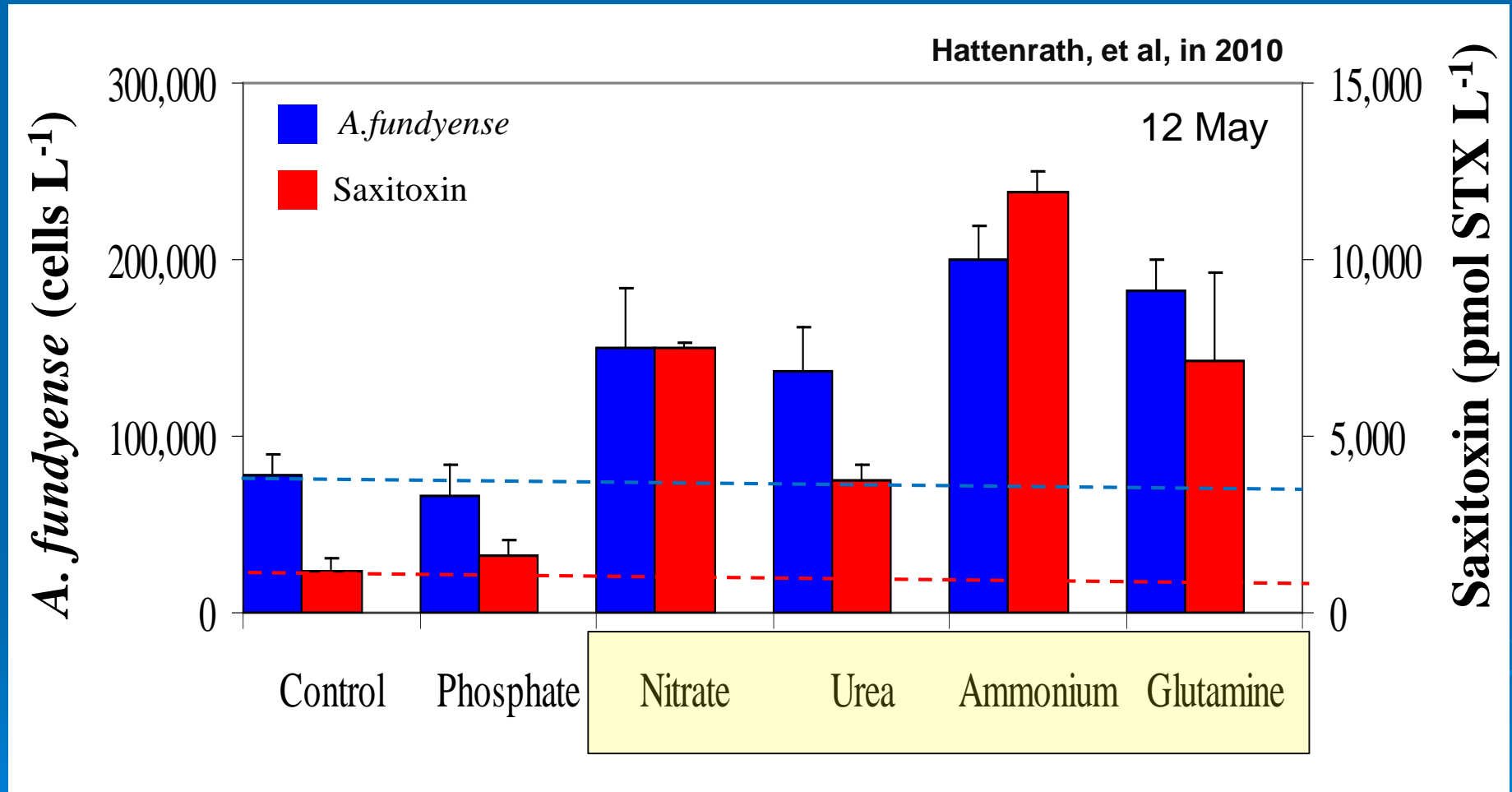
• **7,000 acre closure in Northport – Huntington Bay**

• **> 1 mg STX / 100 g tissue (lethal)**

Marine Biotoxin Closure  
as of May 28, 2008  
Shellfish Harvest Area NS3



# Impact of nutrient loading on *Alexandrium* densities and toxicity



- N increased both *Alexandrium* densities and toxicity

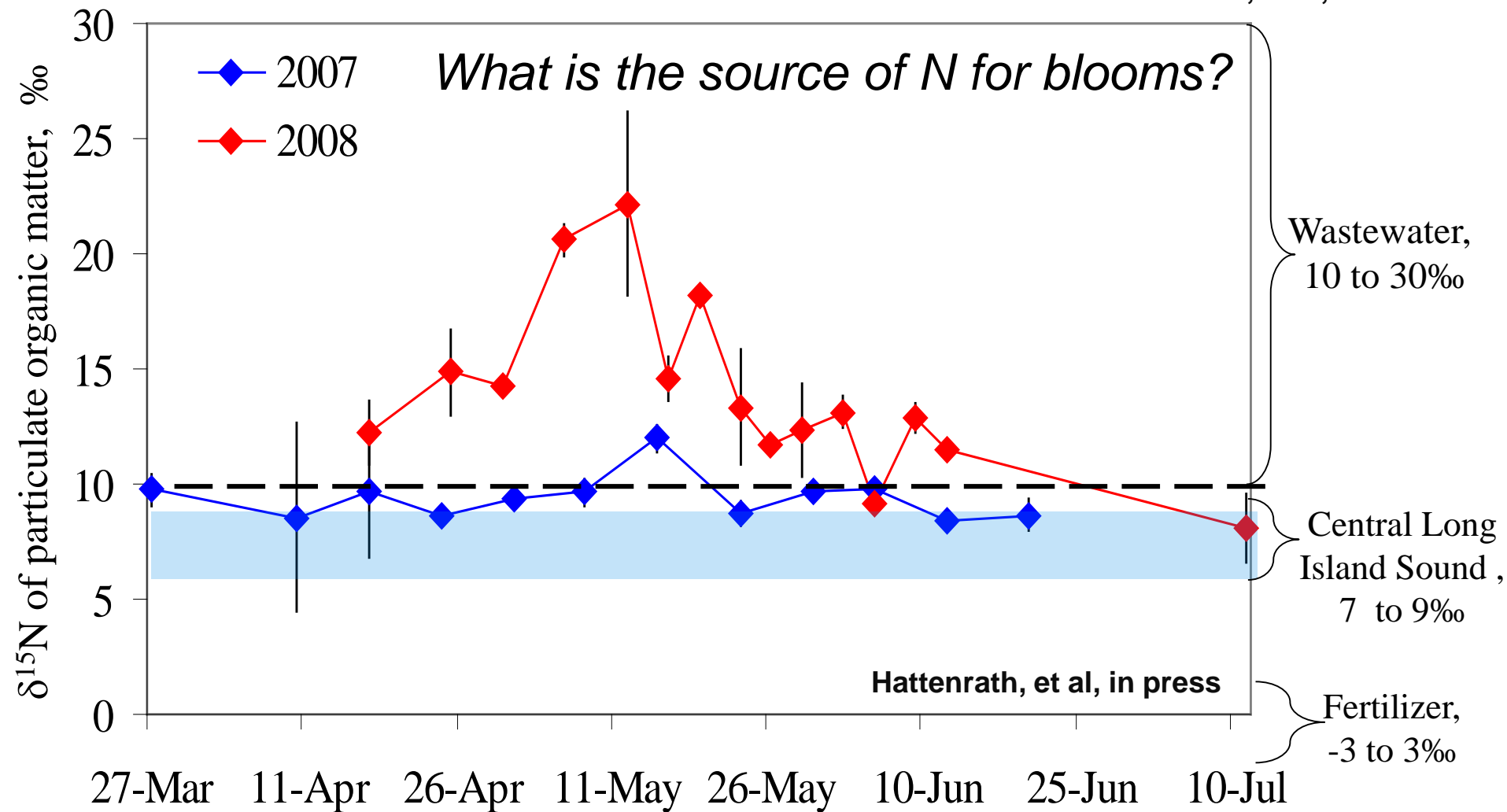
# *What are the sources of nitrogen to blooms?*





# $\delta^{15}\text{N}$ of particulate organic matter from Northport Harbor

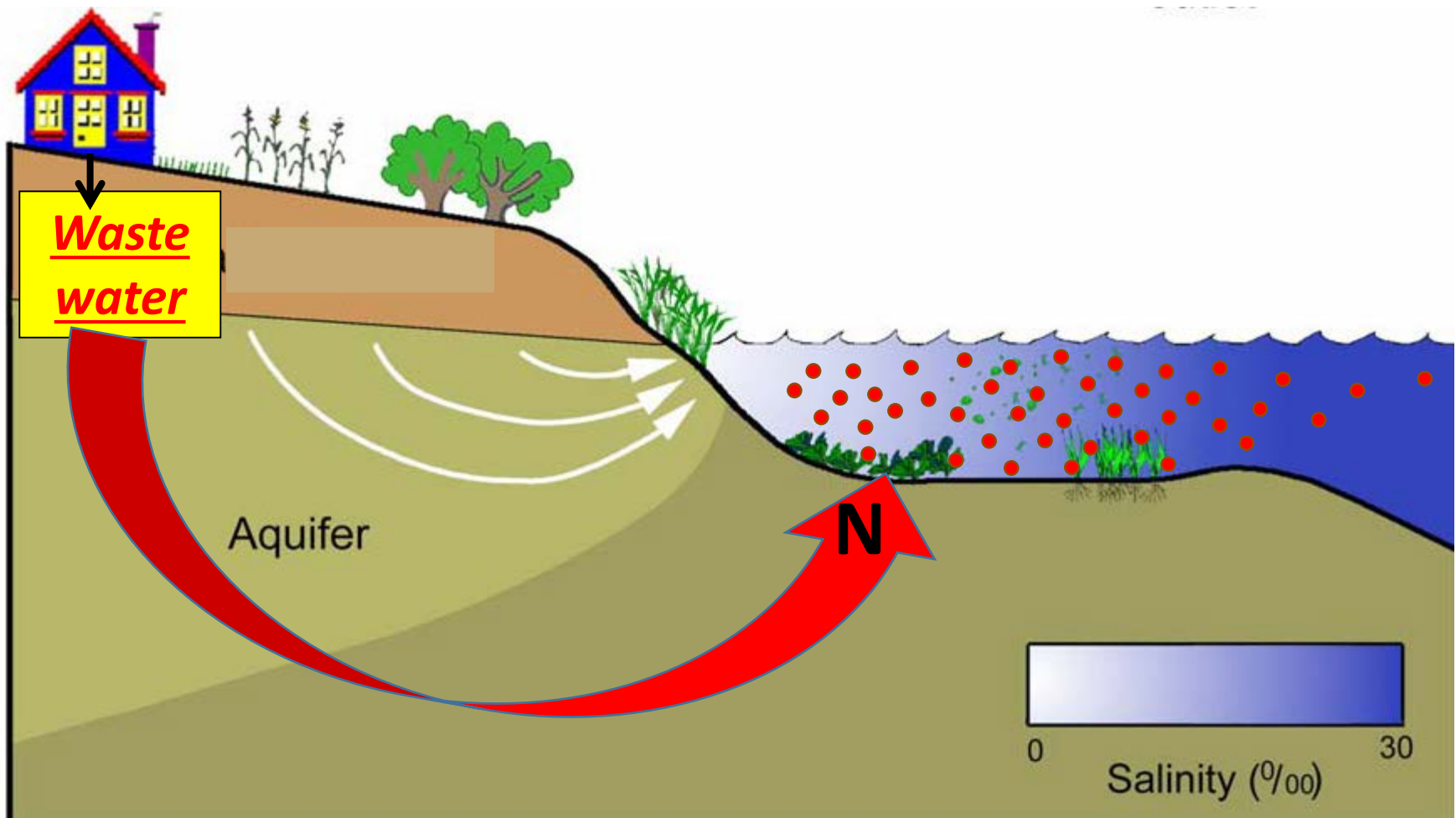
Hattenrath, et al, in 2010



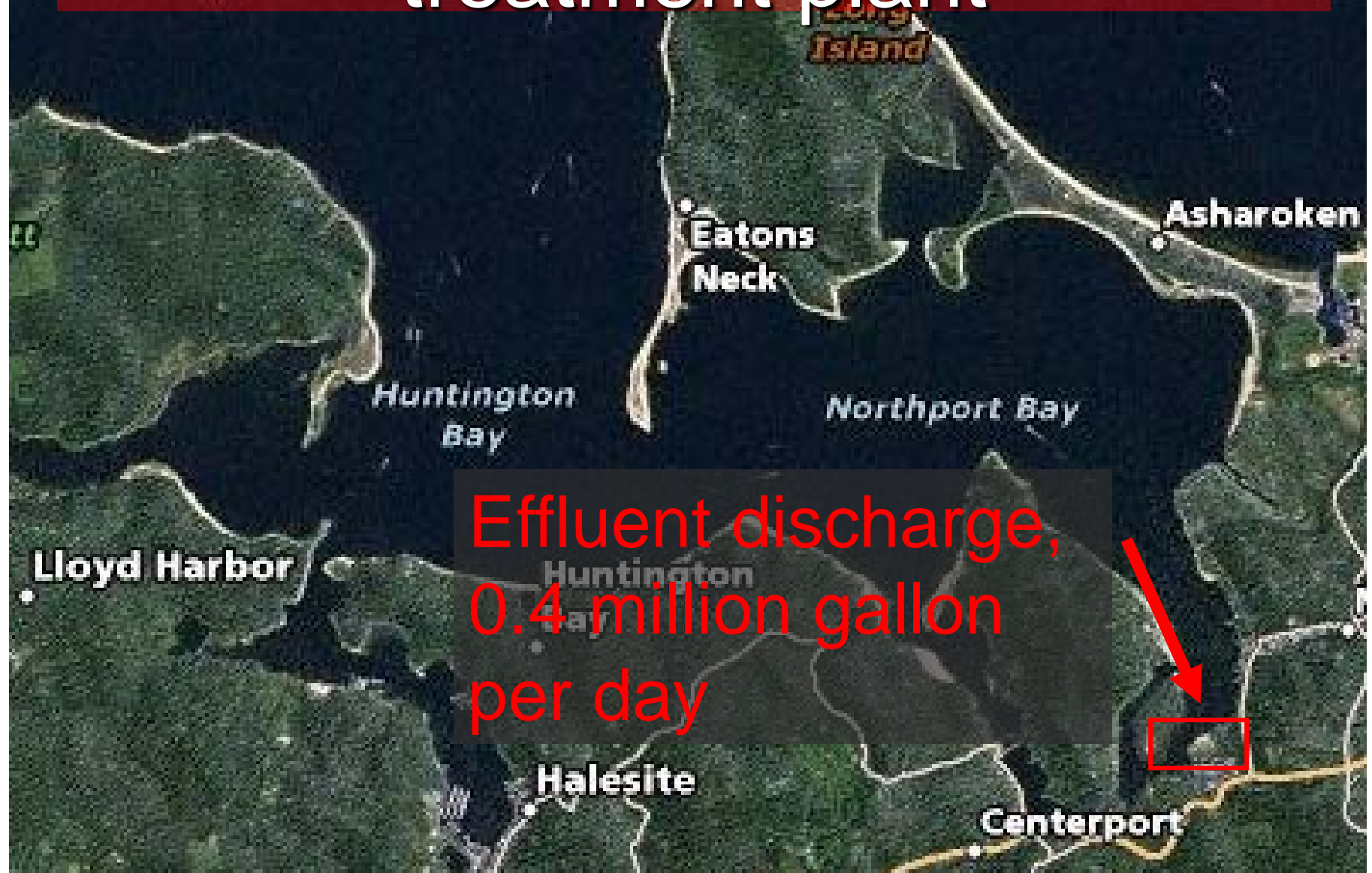
$\delta^{15}\text{N}$  of particulate organic matter was significantly ( $p < 0.001$ ) correlated to *A. fundyense* cell densities and saxitoxin, suggesting that blooms are using wastewater derived N

# Wastewater-derived nitrogen loading promotes PSP in Long Island Sound.

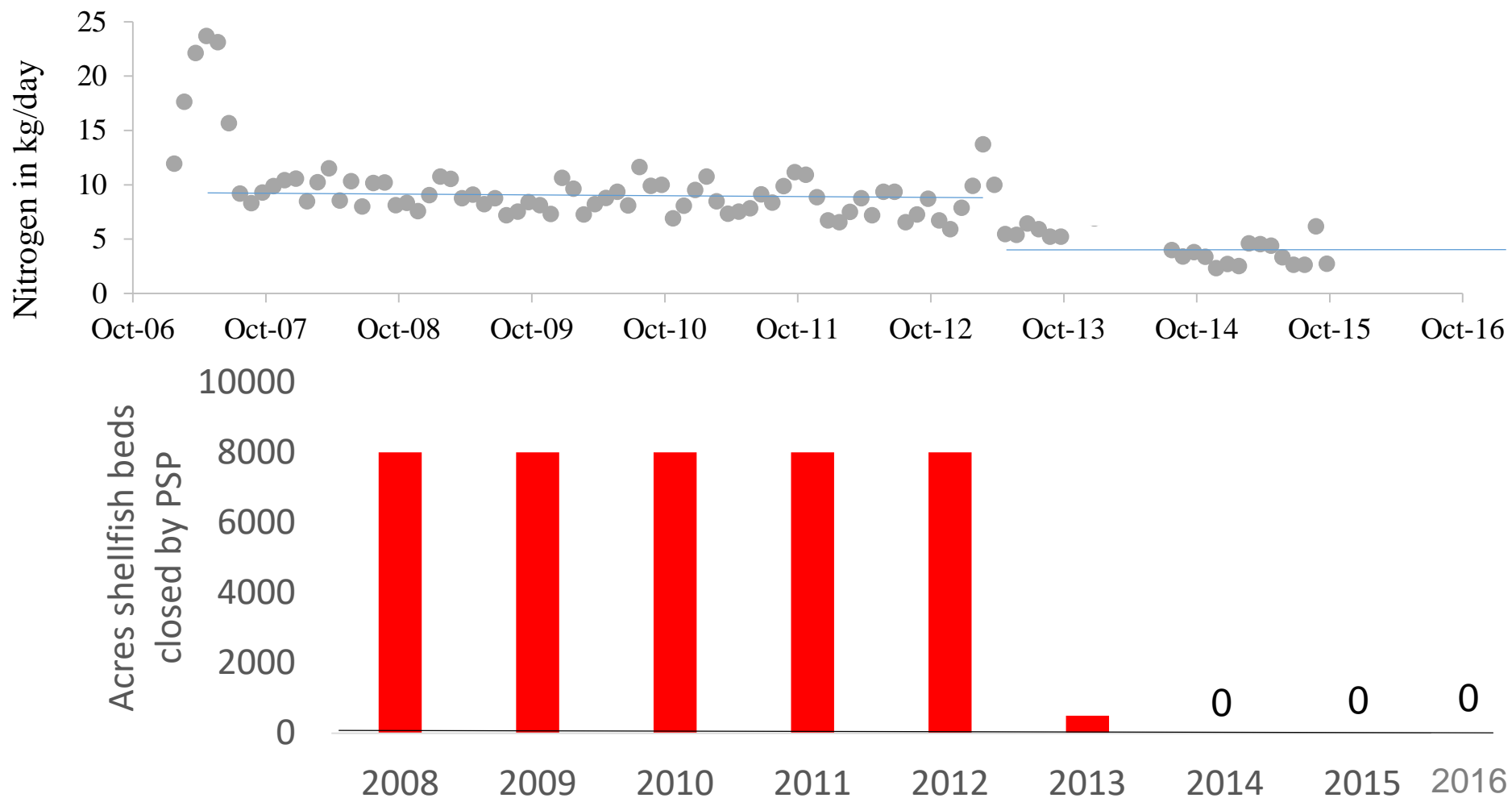
-Hattenrath et al 2010, Harmful Algae



# Scudder Beach sewage treatment plant



# Acres of shellfish beds closed by PSP

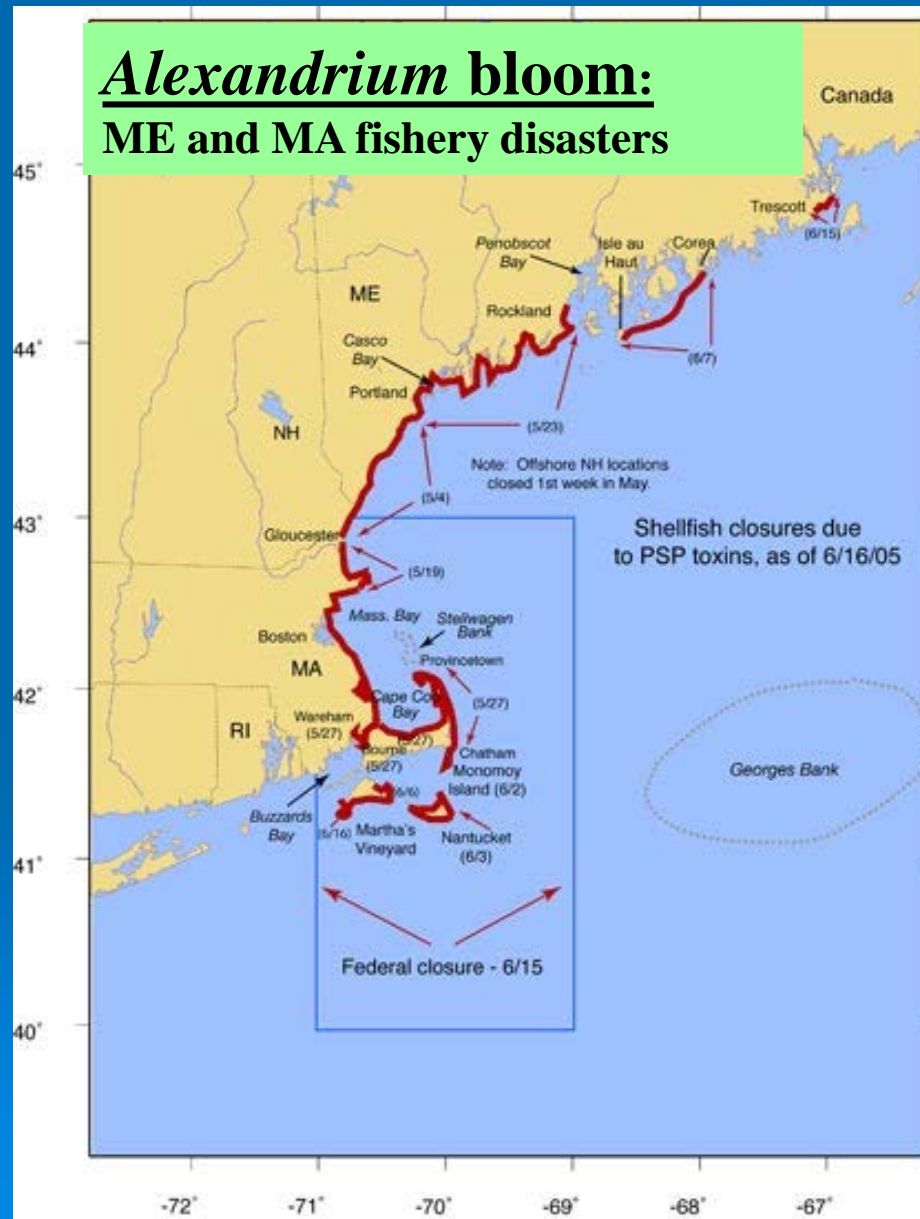


# *Alexandrium* blooms in northeast, USA



# PSP in Gulf of Maine:

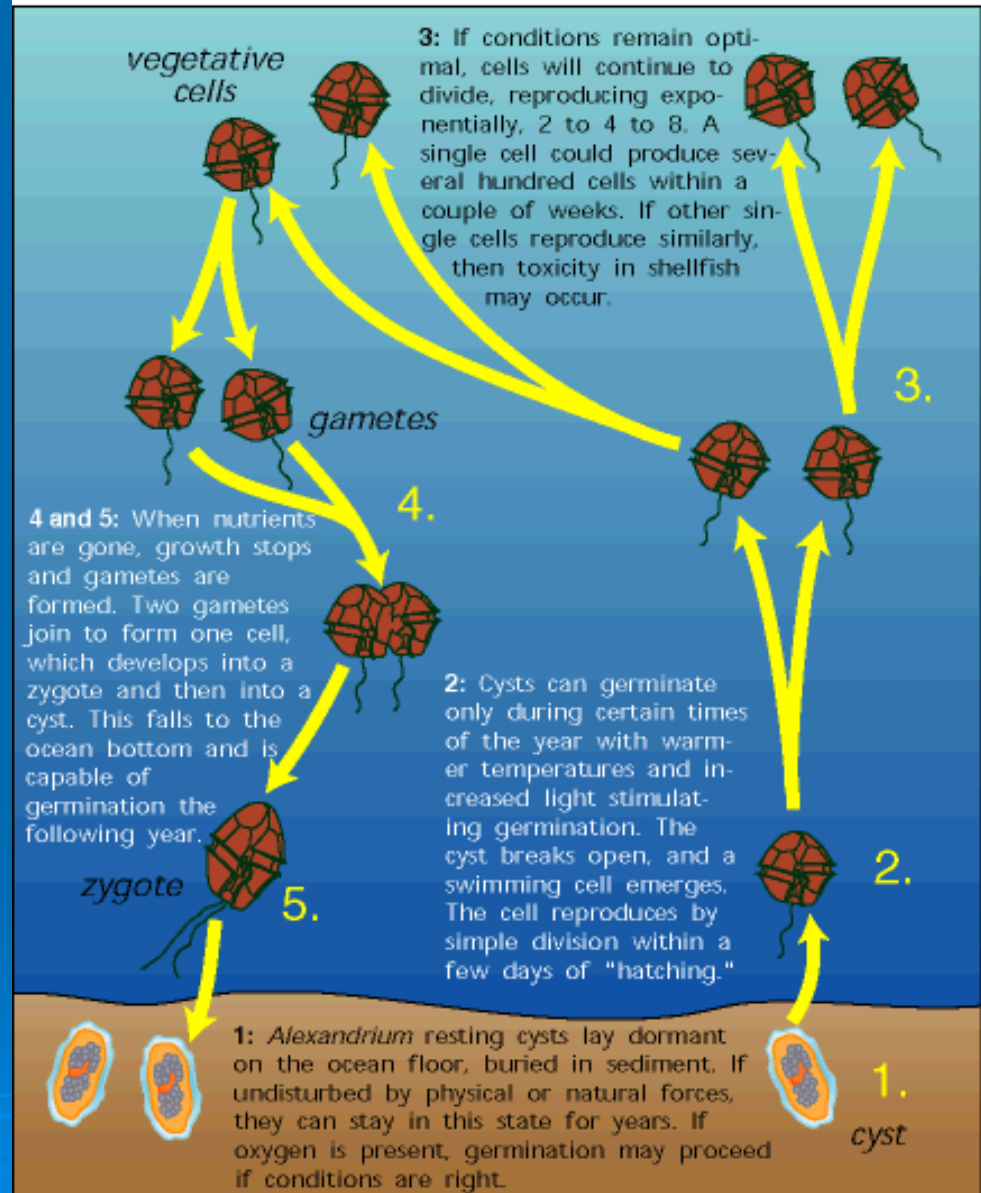
## *Alexandrium* bloom: ME and MA fishery disasters



# Alexandrium sp. Life History Strategy

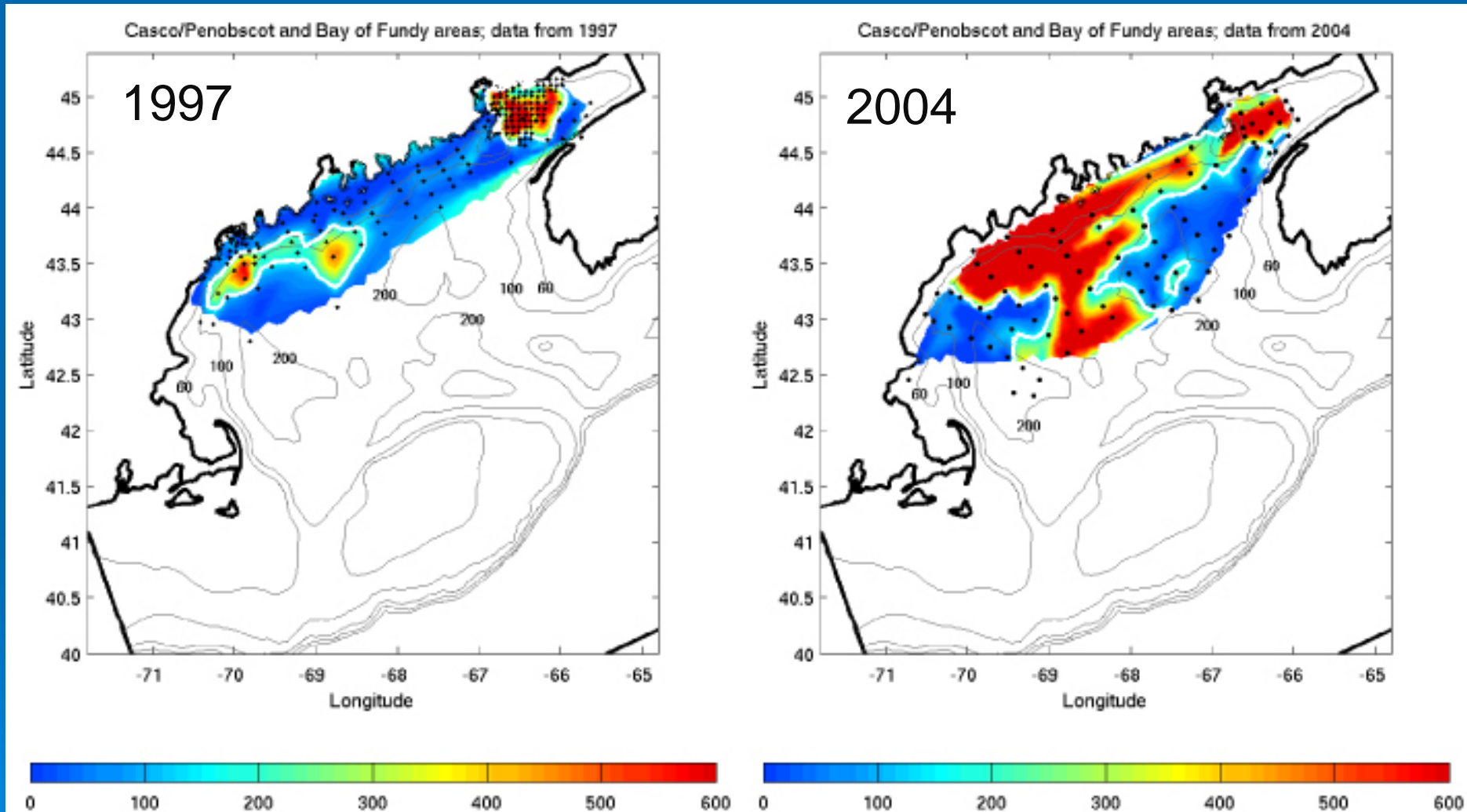
- Cyst formation is a critical life stage adaptation for many dinoflagellate blooms.

## How a Toxic Algal Bloom Occurs *The life cycle of one cell*



 In the Gulf of Maine, cysts beds are the best predictor of blooms.

- Models do not require a nutrient-dependent growth rate.
- Nutrients do not affect bloom (Anderson et al 2008)

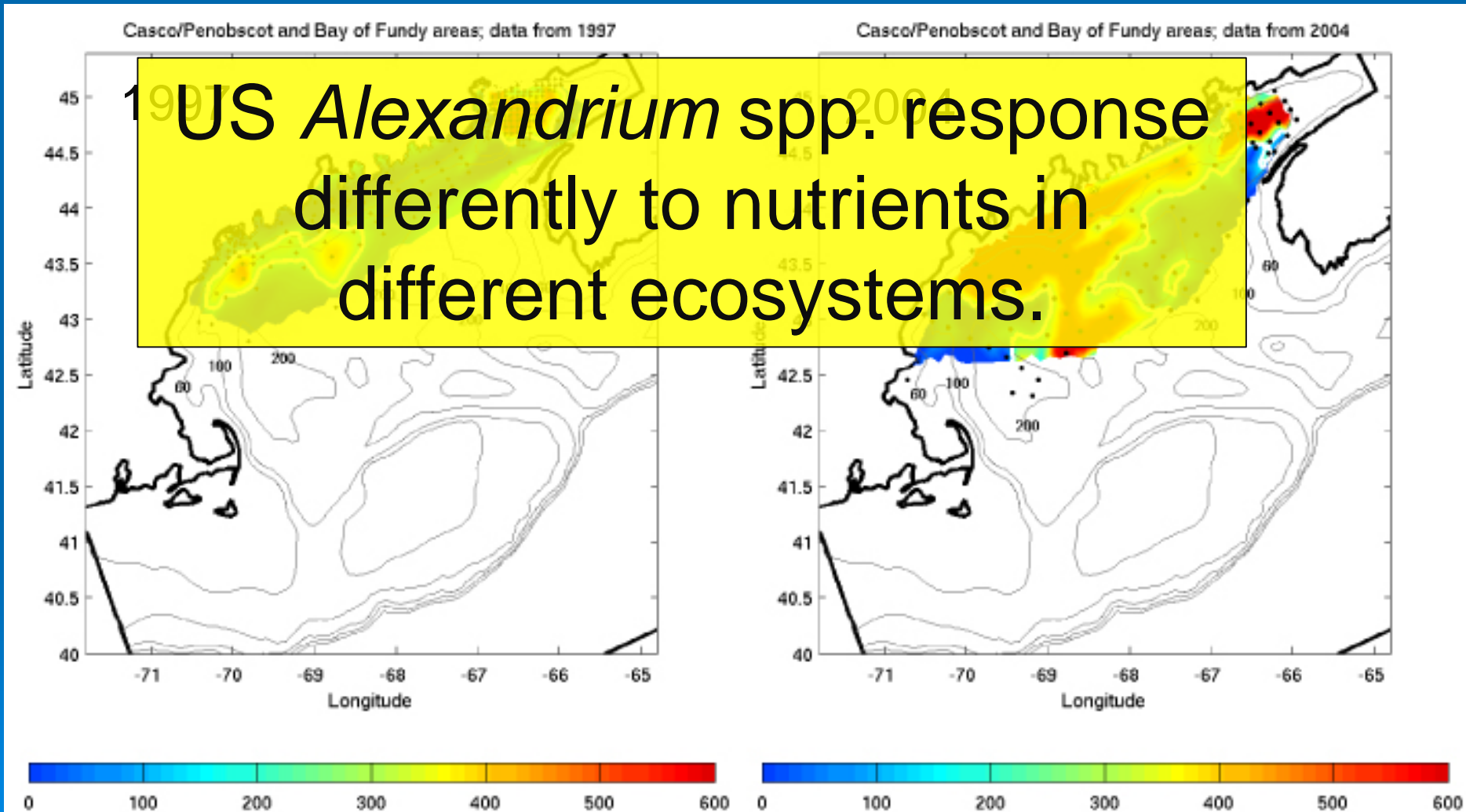


Small bloom in 1998

Large, system-wide bloom in 2005

In the Gulf of Maine, cysts beds are the best predictor of blooms.

- Models do not require a nutrient-dependent growth rate.
- Nutrients do not effect bloom (Anderson et al 2008)

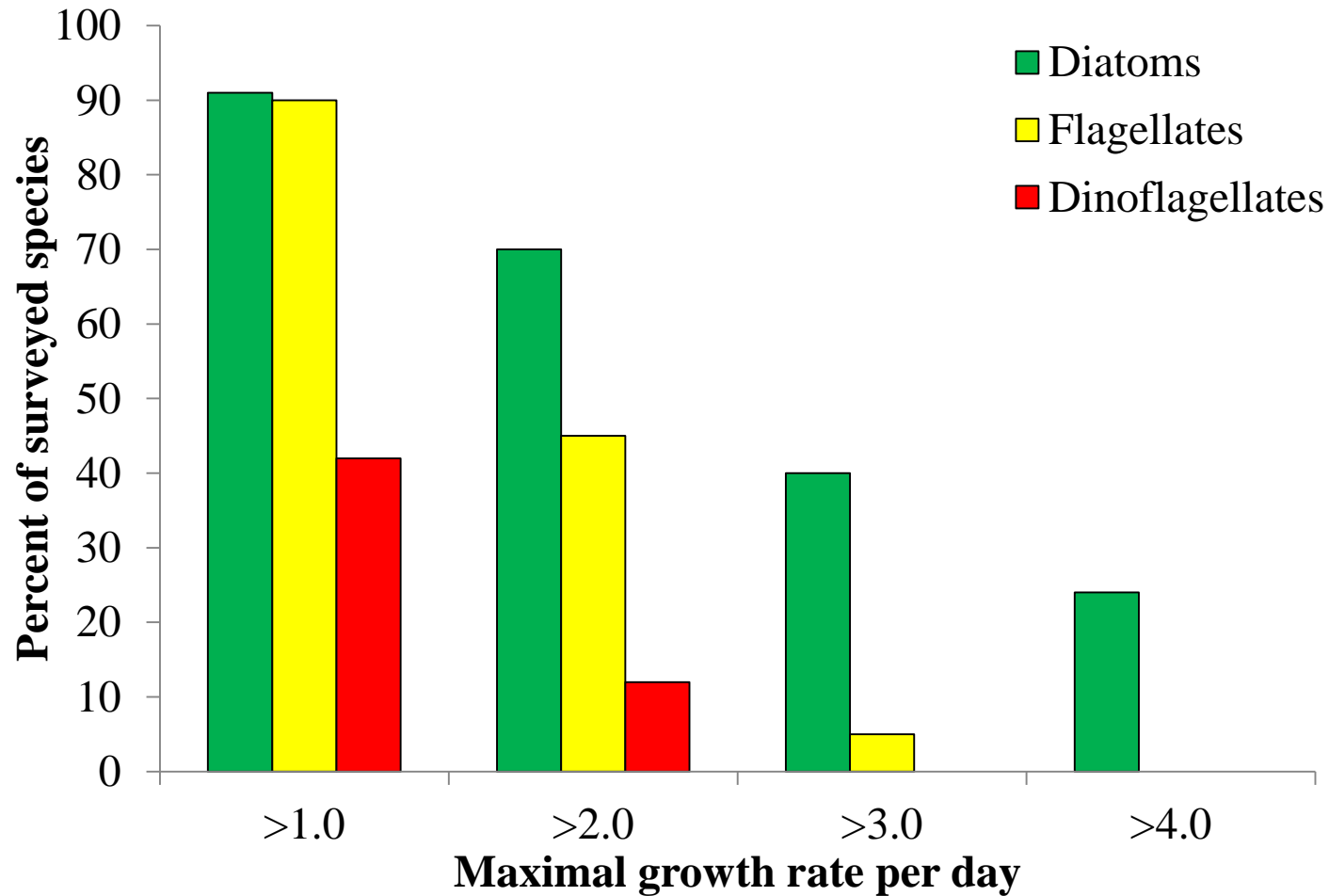


Small bloom in 1998

Large, system-wide bloom in 2005

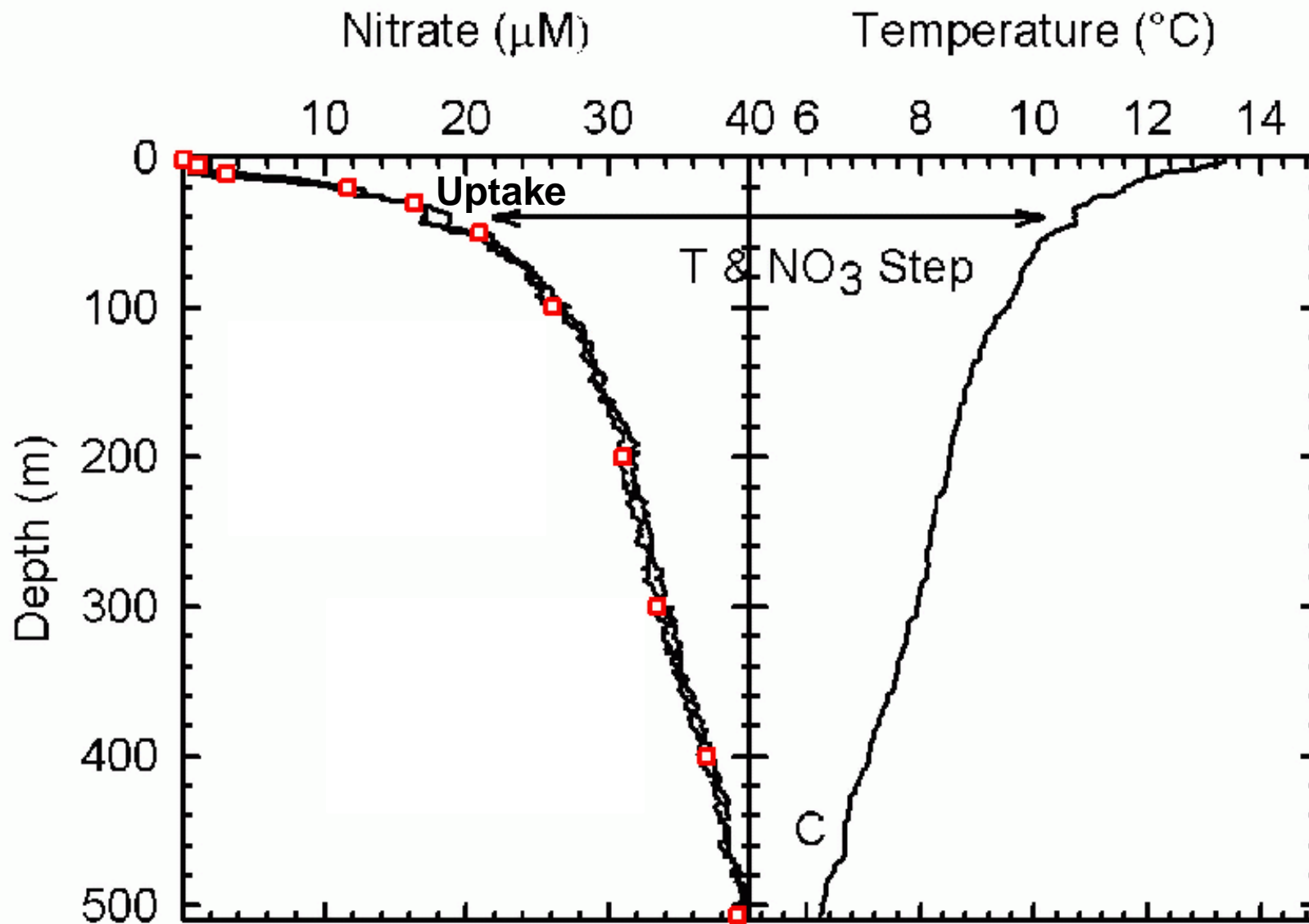
*Some HABs dominate when  
inorganic nutrient levels are  
low...*

# Absent of nutrient limitation, diatoms grow fastest.

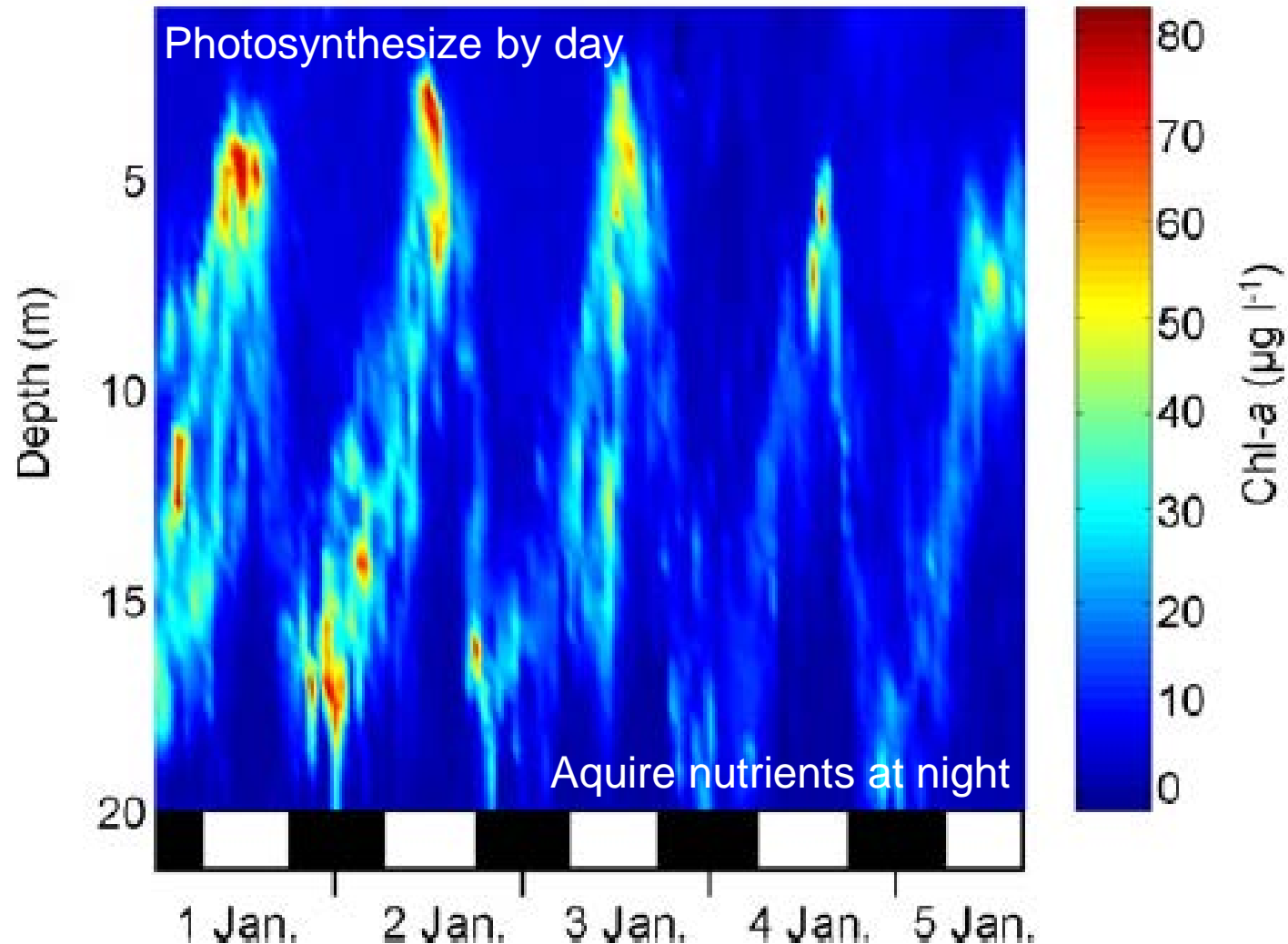


Smayda 1997, 100 species surveyed

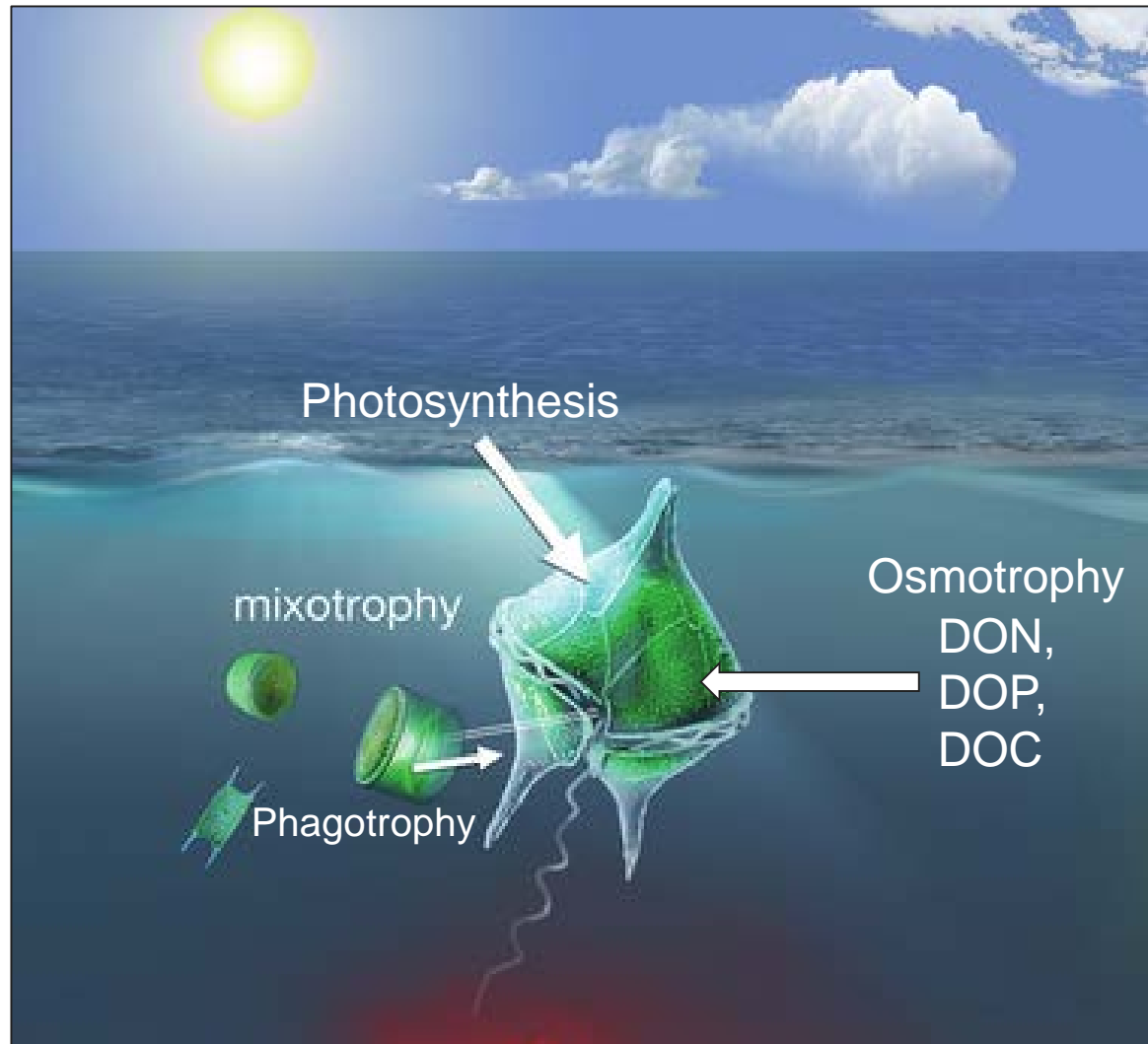
# Vertical trends in nutrients



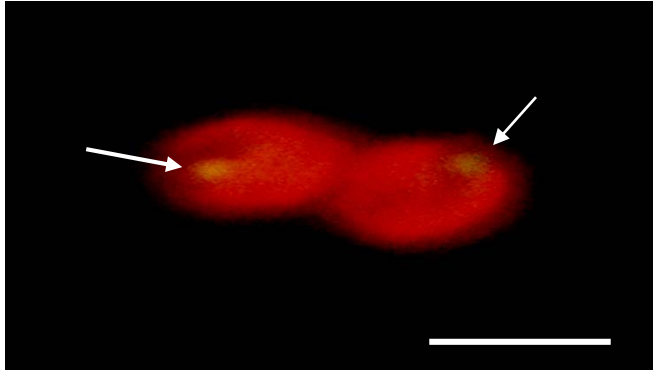
# Diel Vertical Migration, *Gymnodinium catenatum*



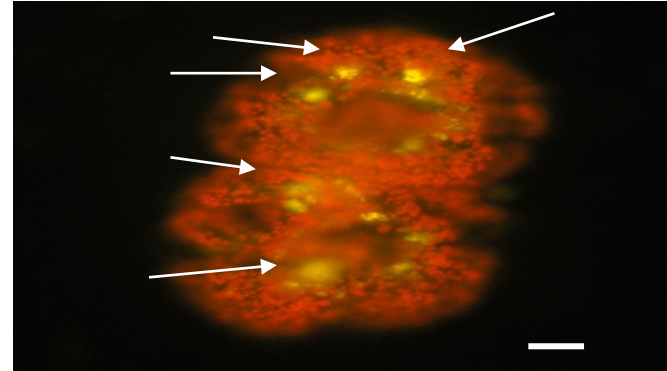
Most marine HABs are dinoflagellates;  
most dinoflagellates are **mixotrophic**.



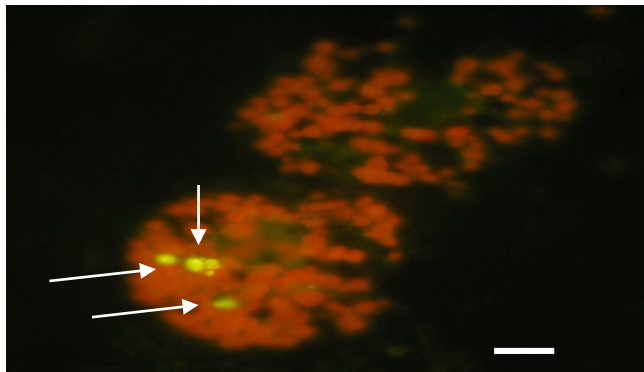
# Feeding by mixotrophic dinoflagellates on cyanobacteria *Synechococcus*



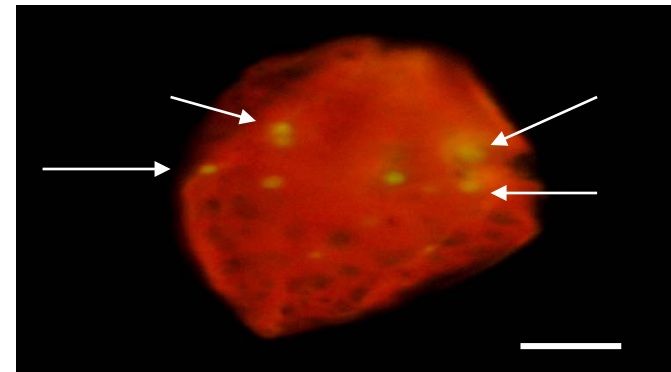
*Heterocapsa rotundata*



*Gymnodinium catenatum*



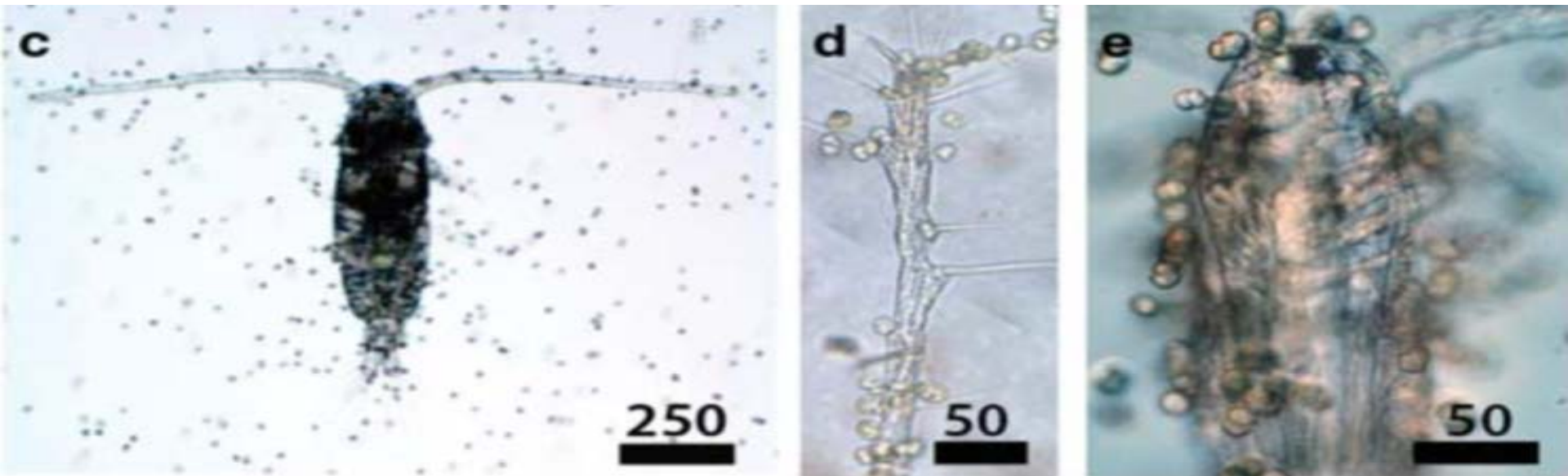
*Cochlodinium polykrikoides*



*Prorocentrum micans*

Scale bar = 10  $\mu$ m

Protists can ingest prey of equal or larger size than themselves



Berge et al. 2012

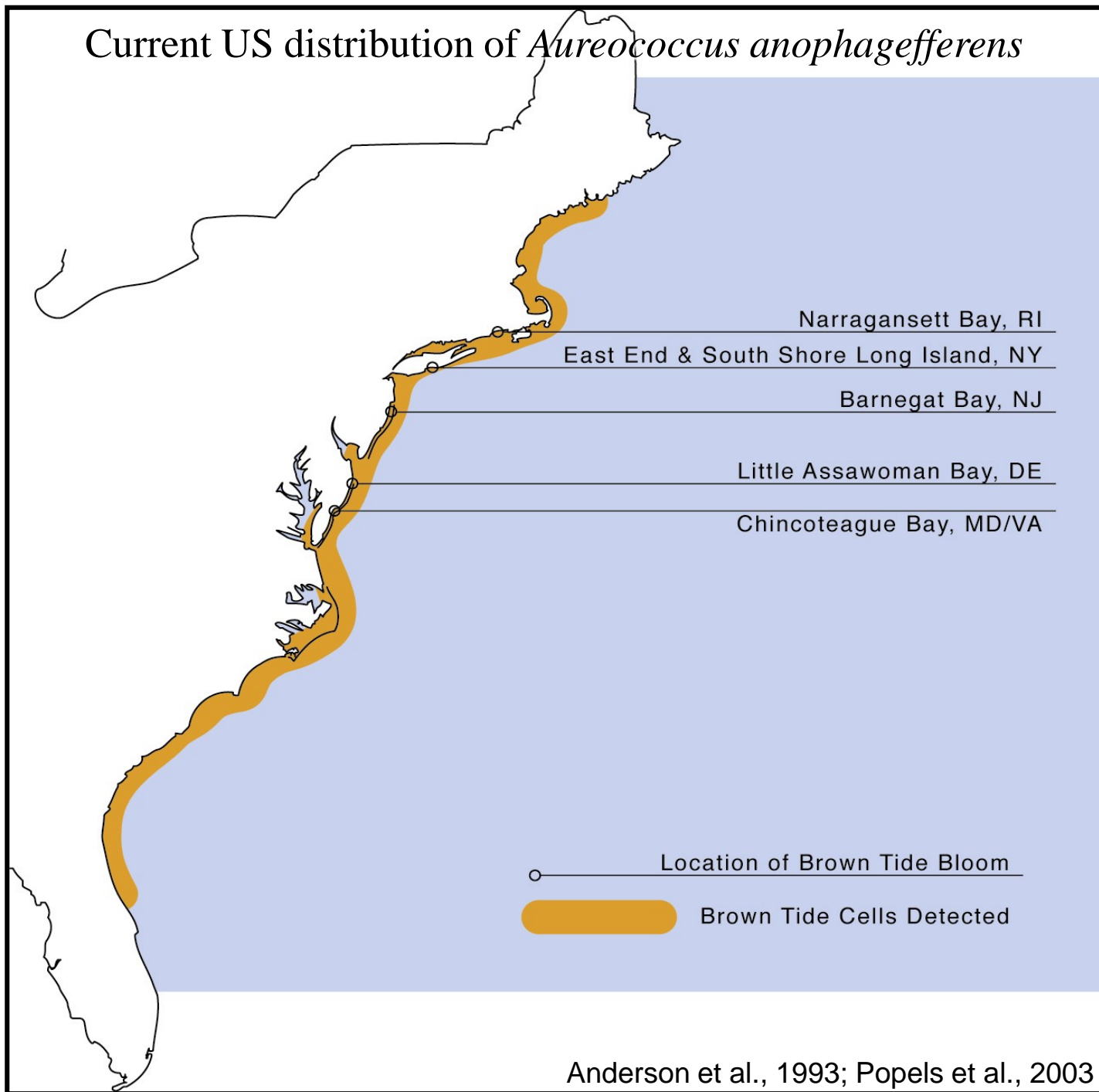
Dinoflagellate *K. armiger* swarms and attacks a copepod

*Some non-dinoflagellate  
HABs also dominate when  
inorganic nutrient levels are  
low...*

# Brown tide

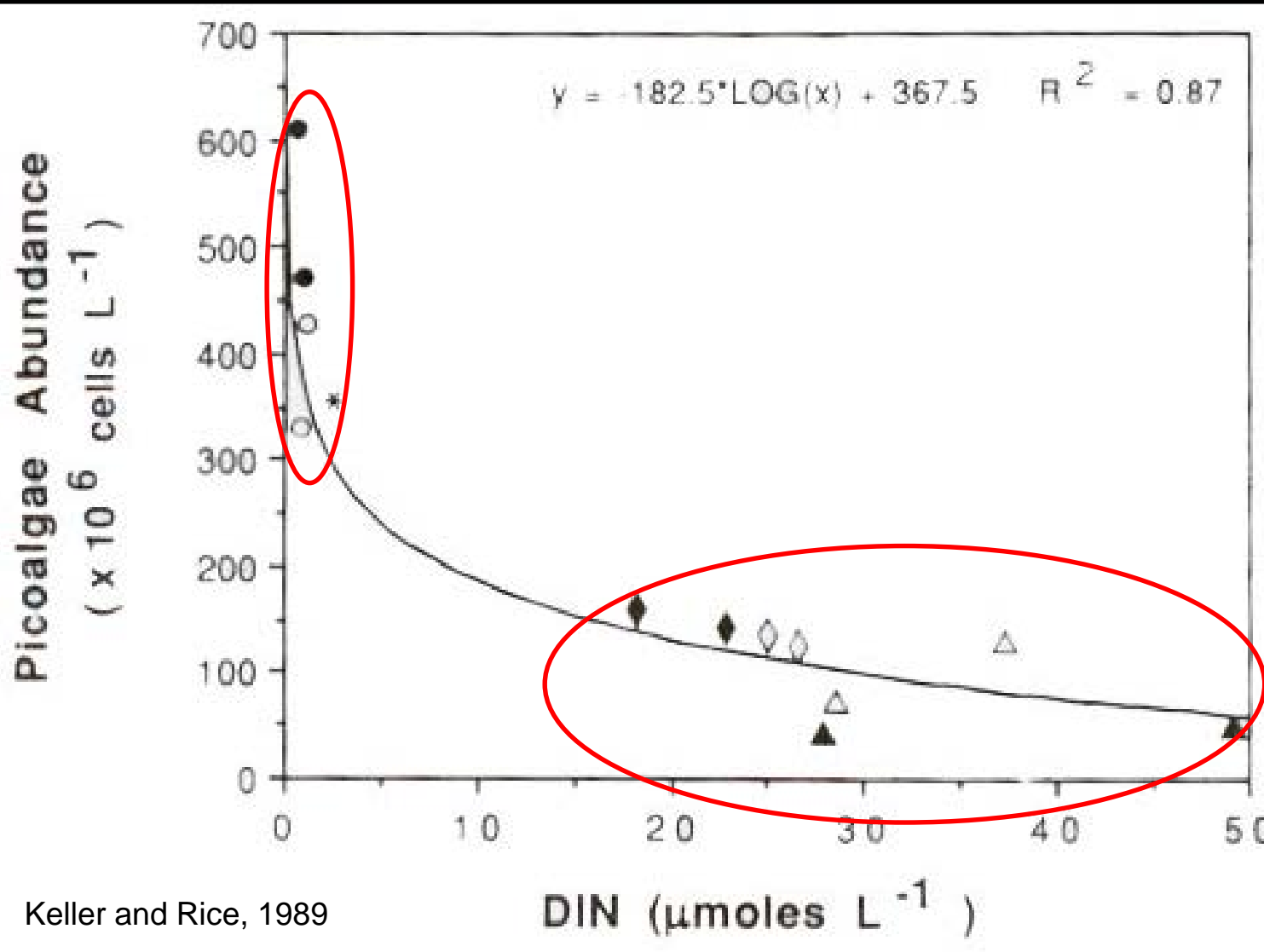


# Current US distribution of *Aureococcus anophagefferens*

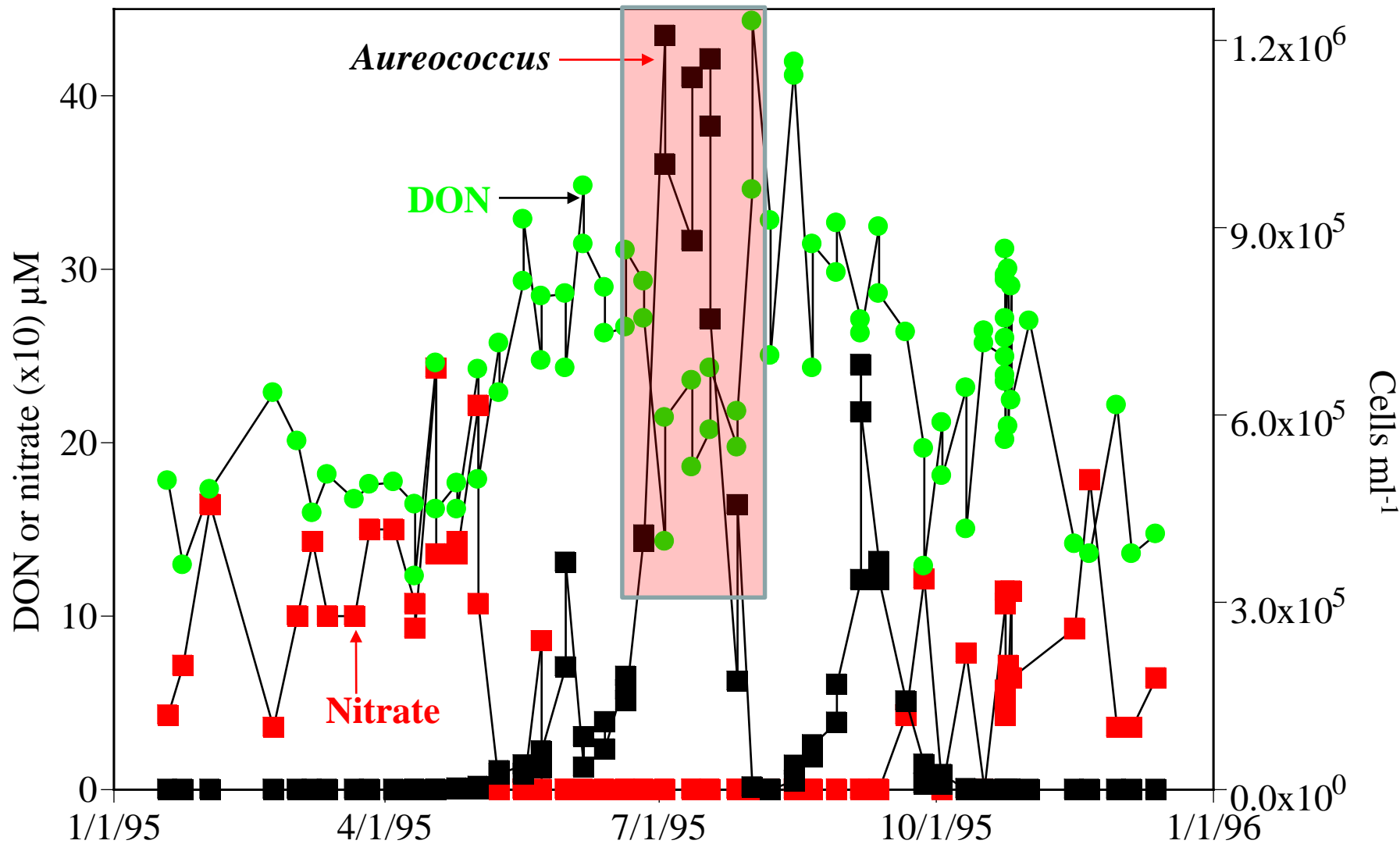


Anderson et al., 1993; Popels et al., 2003

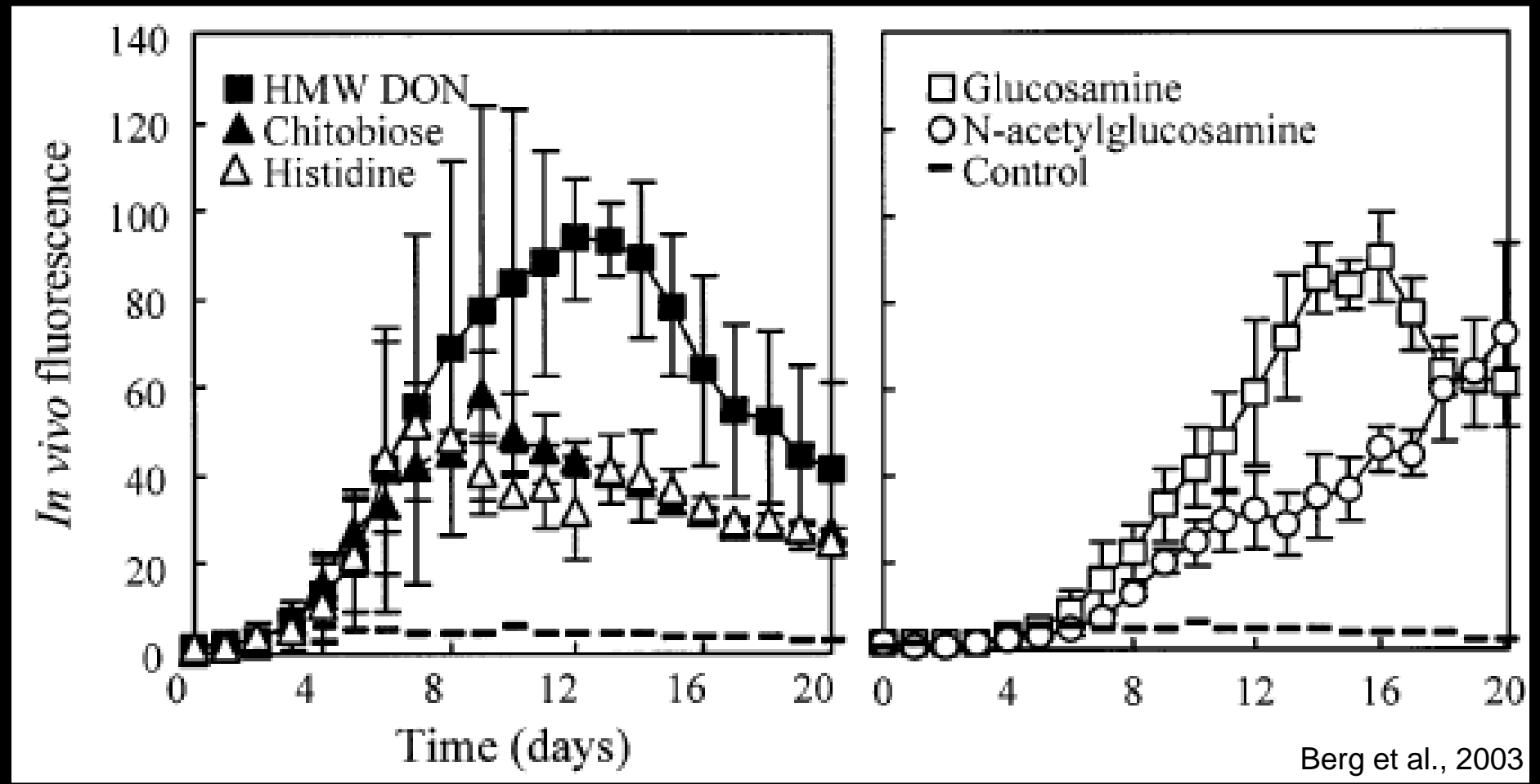
Unlike other algal blooms, brown tides are not caused by inorganic nitrogen loading...



# Organic nutrients and brown tide



Growth of axenic *A. anophagefferens* cultures exclusively on complex, organic nitrogen

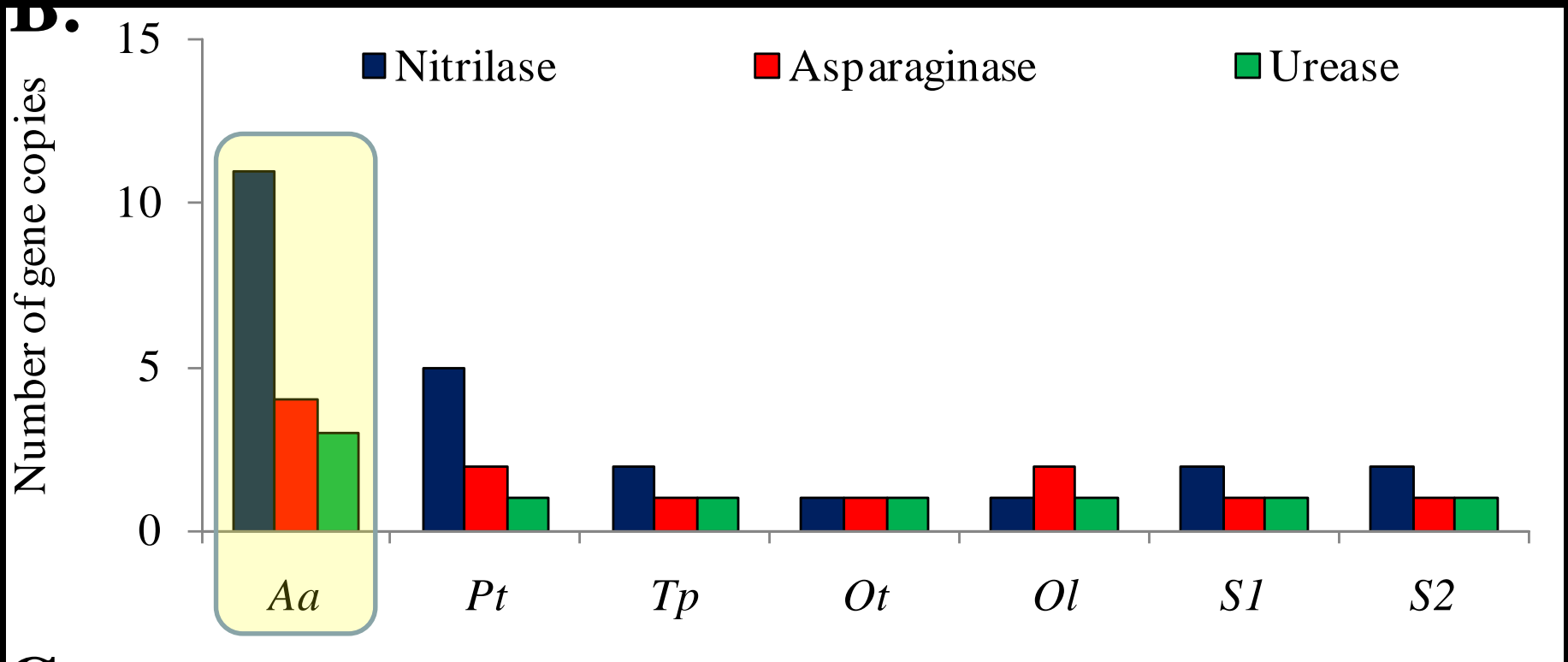


# Nutrients and the *Aureococcus* genome

## Niche of harmful alga *Aureococcus anophagefferens* revealed through ecogenomics

Christopher J. Gobler<sup>a,b,1</sup>, Dianna L. Berry<sup>a,b,2</sup>, Sonya T. Dyhrman<sup>c,2</sup>, Steven W. Wilhelm<sup>d,2</sup>, Asaf Salamov<sup>e</sup>, Alexei V. Lobanov<sup>f</sup>, Yan Zhang<sup>f</sup>, Jackie L. Collier<sup>b</sup>, Louie L. Wurch<sup>c</sup>, Adam B. Kustka<sup>g</sup>, Brian D. Dill<sup>h</sup>, Manesh Shah<sup>i</sup>, Nathan C. VerBerkmoes<sup>h</sup>, Alan Kuo<sup>e</sup>, Astrid Terry<sup>e</sup>, Jasmyrn Pangilinan<sup>e</sup>, Erika A. Lindquist<sup>e</sup>, Susan Lucas<sup>e</sup>, Ian T. Paulsen<sup>j</sup>, Theresa K. Hattenrath-Lehmann<sup>a,b</sup>, Stephanie C. Talmage<sup>a,b</sup>, Elyse A. Walker<sup>a,b</sup>, Florian Koch<sup>a,b</sup>, Amanda M. Burson<sup>a,b</sup>, Maria Alejandra Marcoval<sup>a,b</sup>, Ying-Zhong Tang<sup>a,b</sup>, Gary R. LeClerc<sup>c</sup>, Kathryn J. Coyne<sup>k</sup>, Gry M. Berg<sup>l</sup>, Erin M. Bertrand<sup>m</sup>, Mak A. Saito<sup>m,n</sup>, Vadim N. Gladyshev<sup>d</sup>, and Igor V. Grigoriev<sup>e,1</sup>

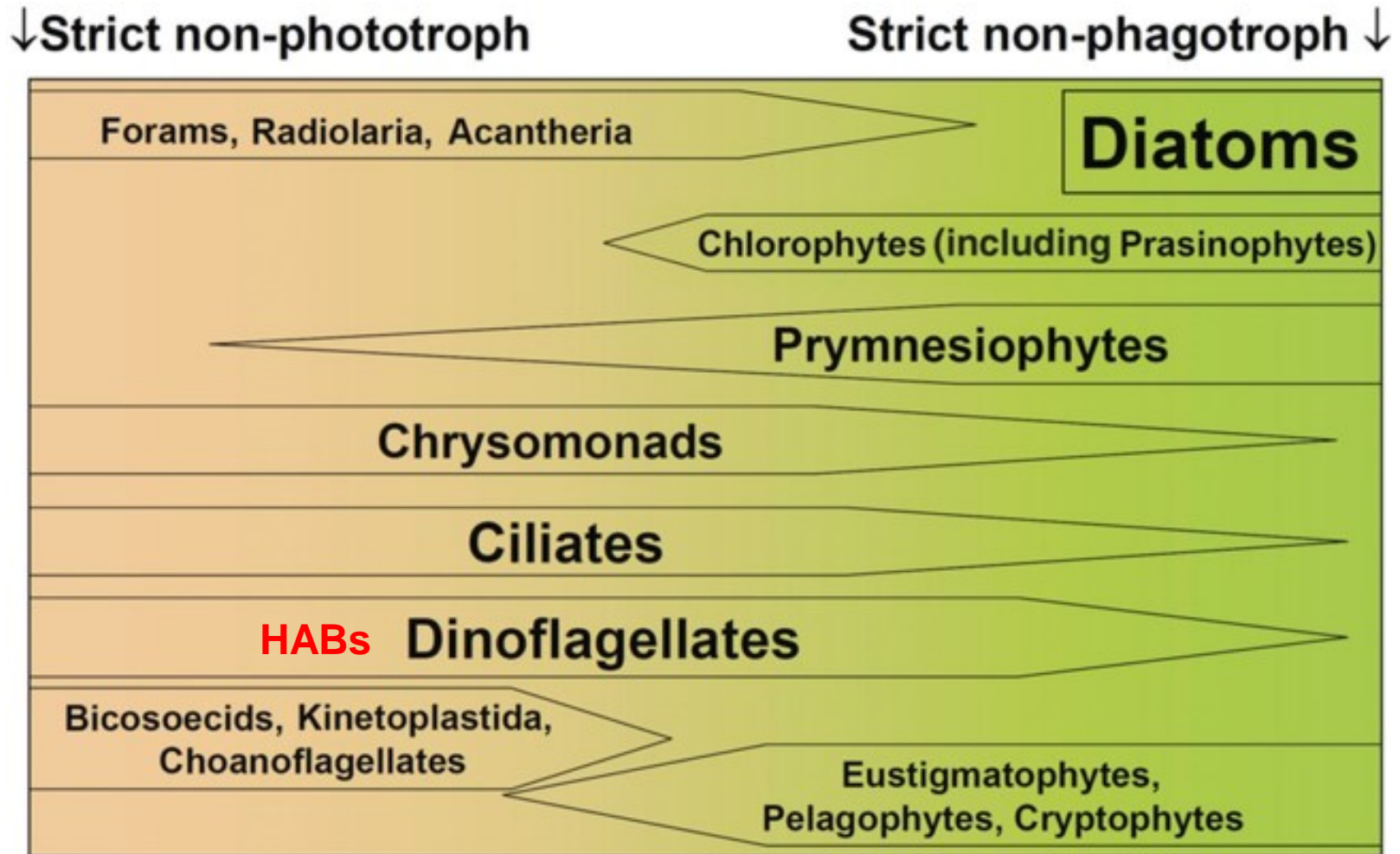
# DON enzymes in *Aureococcus*



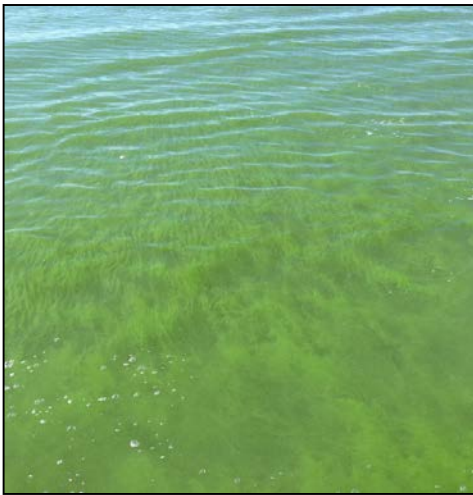
# The organic niche:

- Many phytoplankton species rely on inorganic nutrients and sunlight to grow.
- Genomic, field, and lab studies have demonstrated *A. anophagefferens* can hydrolyze and utilize complex DON and DOC compounds (Mulholland, et al 2002; Berg et al., 1997, 2002, 2003; Fan et al 2003).
- While other species are 'starving' for nitrogen and / or carbon, *A. anophagefferens* can use organic nutrients to grow.

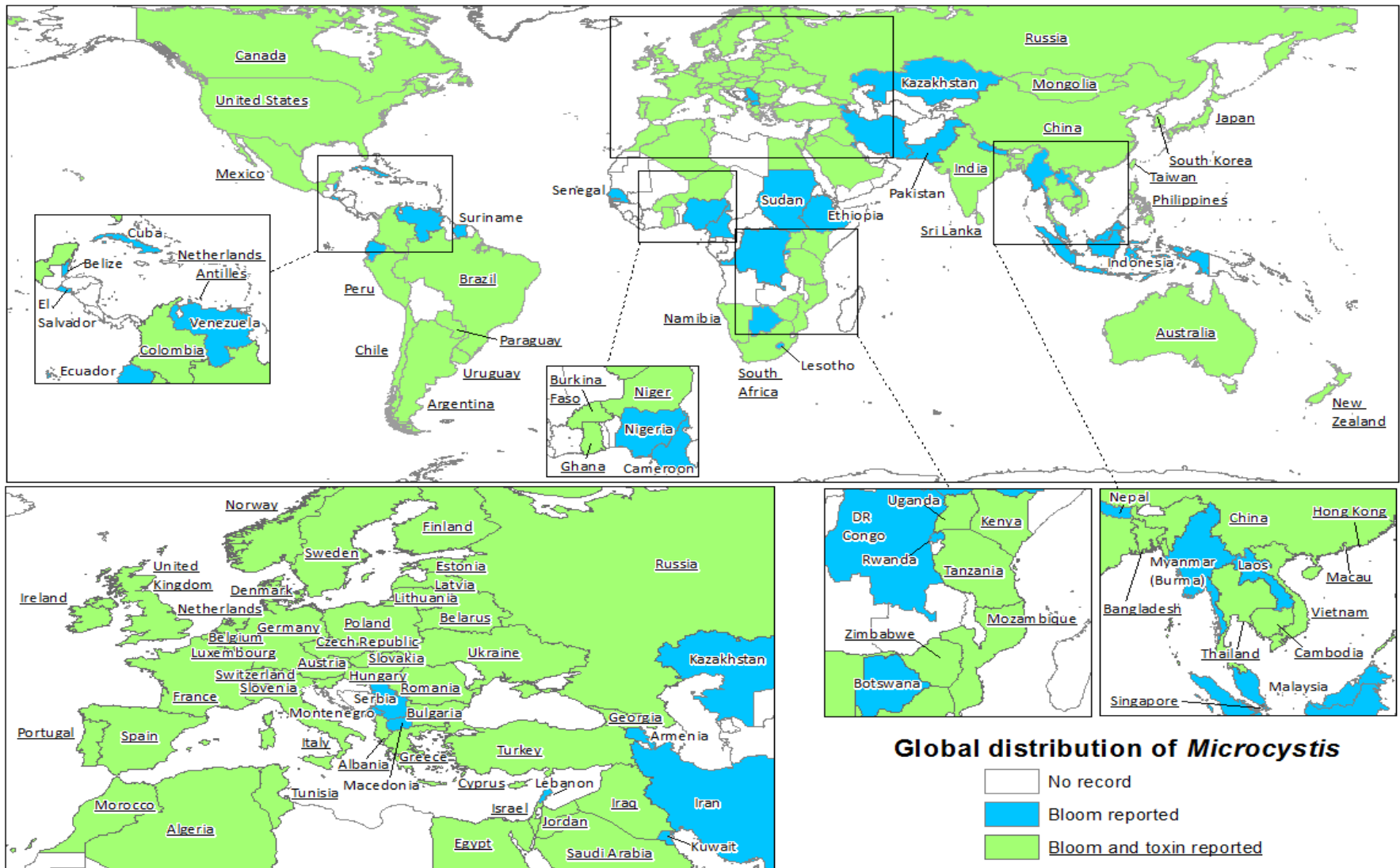
# Heterotrophy among phytoplankton



# N vs P control of cyanobacteria



# Global distribution of *Microcystis*

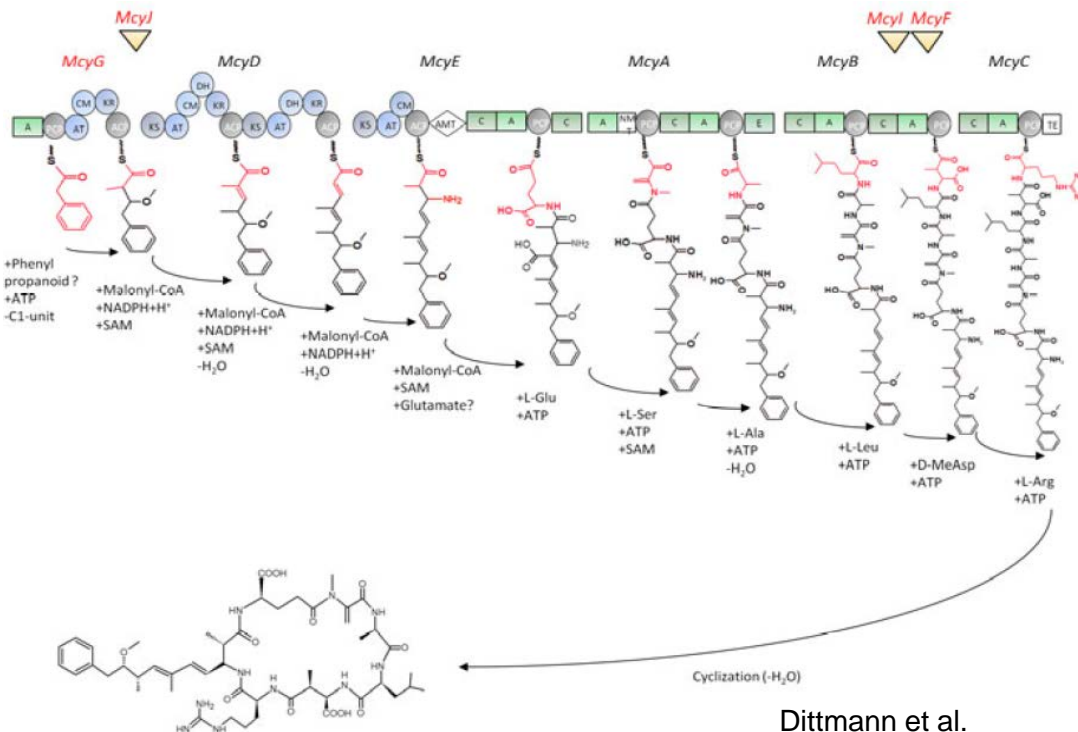


# *Microcystis aeruginosa*

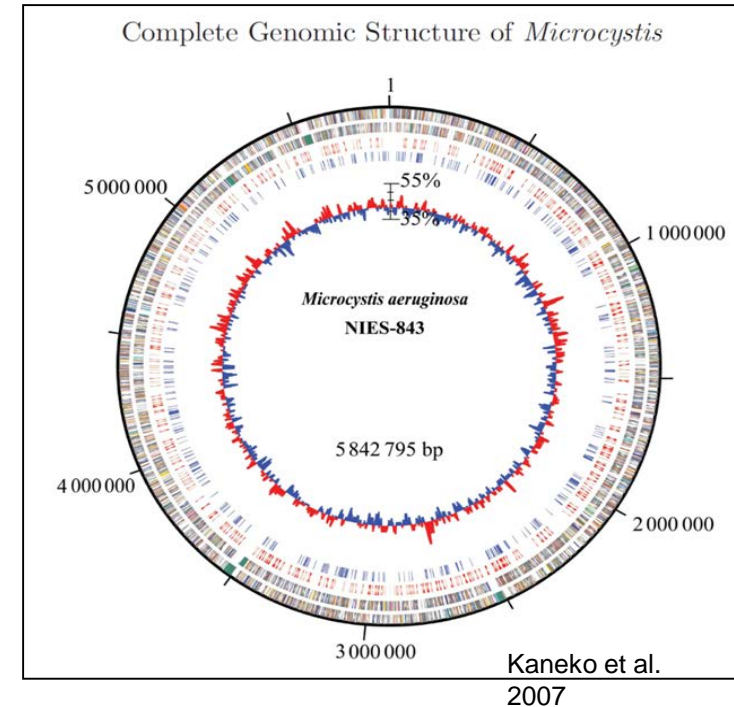
- Produces the hepatotoxin, microcystin; toxin synthesis genes well characterized.
- Sequenced, well-annotated genome available.

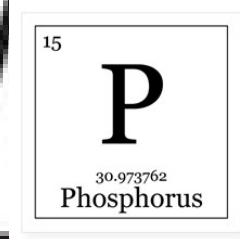
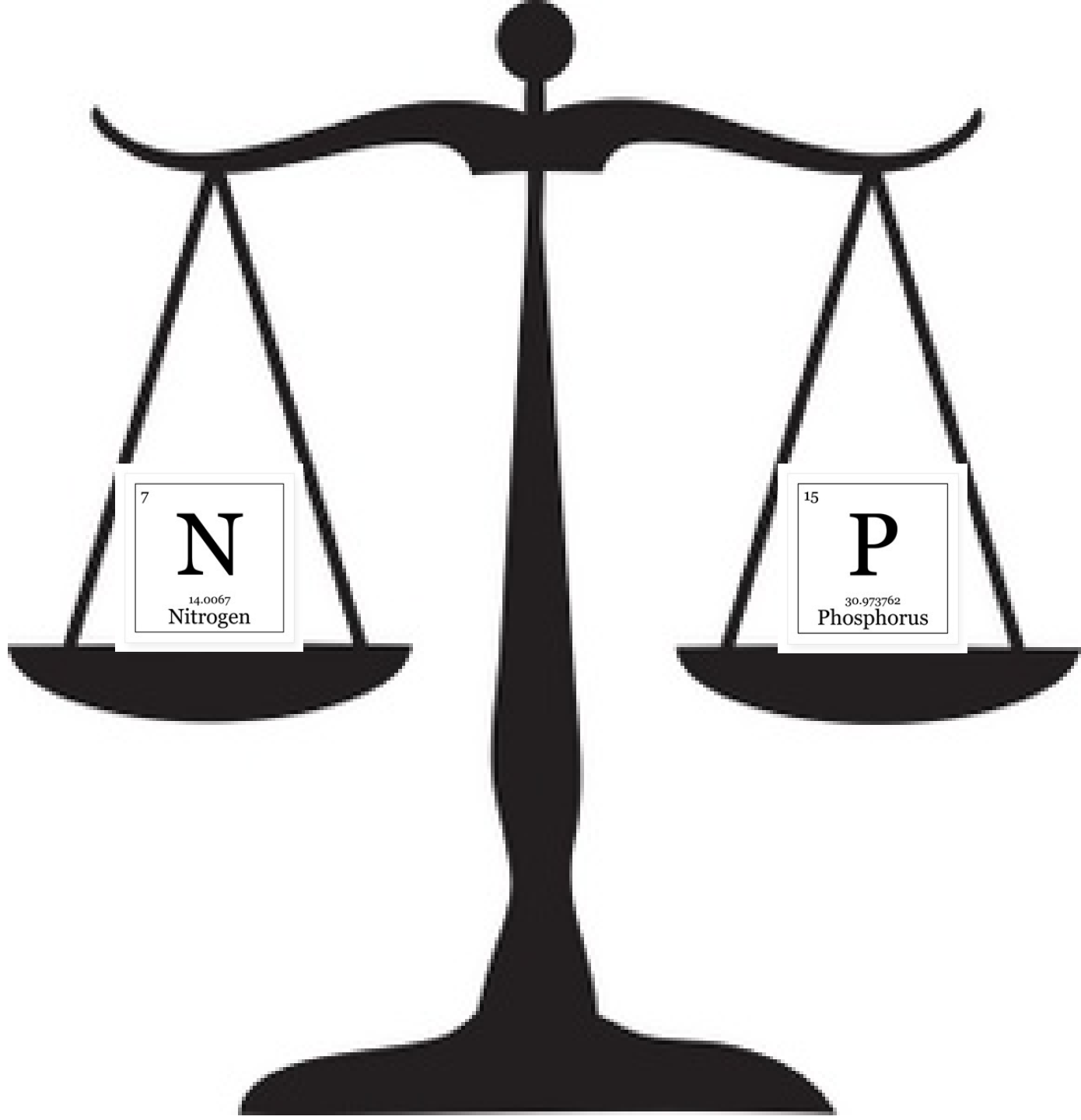


Lake Erie, USA 2013



Dittmann et al.  
2012





# Eutrophication of lakes cannot be controlled by reducing nitrogen input: Results of a 37-year whole-ecosystem experiment

David W. Schindler<sup>\*†</sup>, R. E. Hecky<sup>‡</sup>, D. L. Findlay<sup>§</sup>, M. P. Stainton<sup>§</sup>, B. R. Parker<sup>\*</sup>, M. J. Paterson<sup>§</sup>, K. G. Beaty<sup>§</sup>, M. Lyng<sup>§</sup>, and S. E. M. Kasian<sup>§</sup>

<sup>\*</sup>Department of Biological Sciences, University of Alberta, Edmonton, AB, Canada T6G 2E9; <sup>‡</sup>Department of Biology, University of Minnesota, Duluth, MN 55812; and <sup>§</sup>Freshwater Institute, Canadian Department of Fisheries and Oceans, Winnipeg, MB, Canada R3T 2N6

Contributed by David W. Schindler, May 28, 2008 (sent for review March 25, 2008)

## VS.

POLICY FORUM

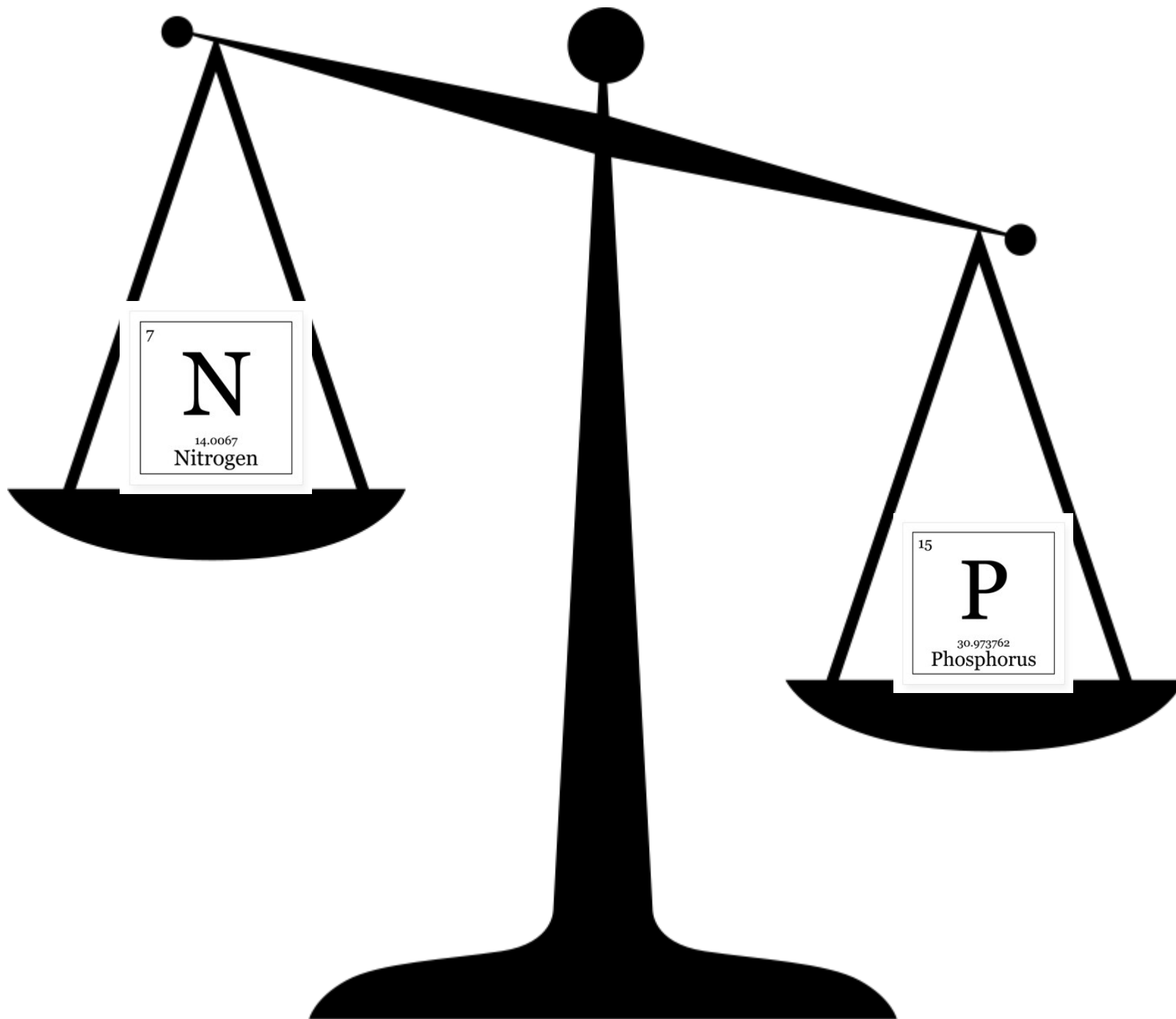
SCIENCE GALLERY

ECOLOGY

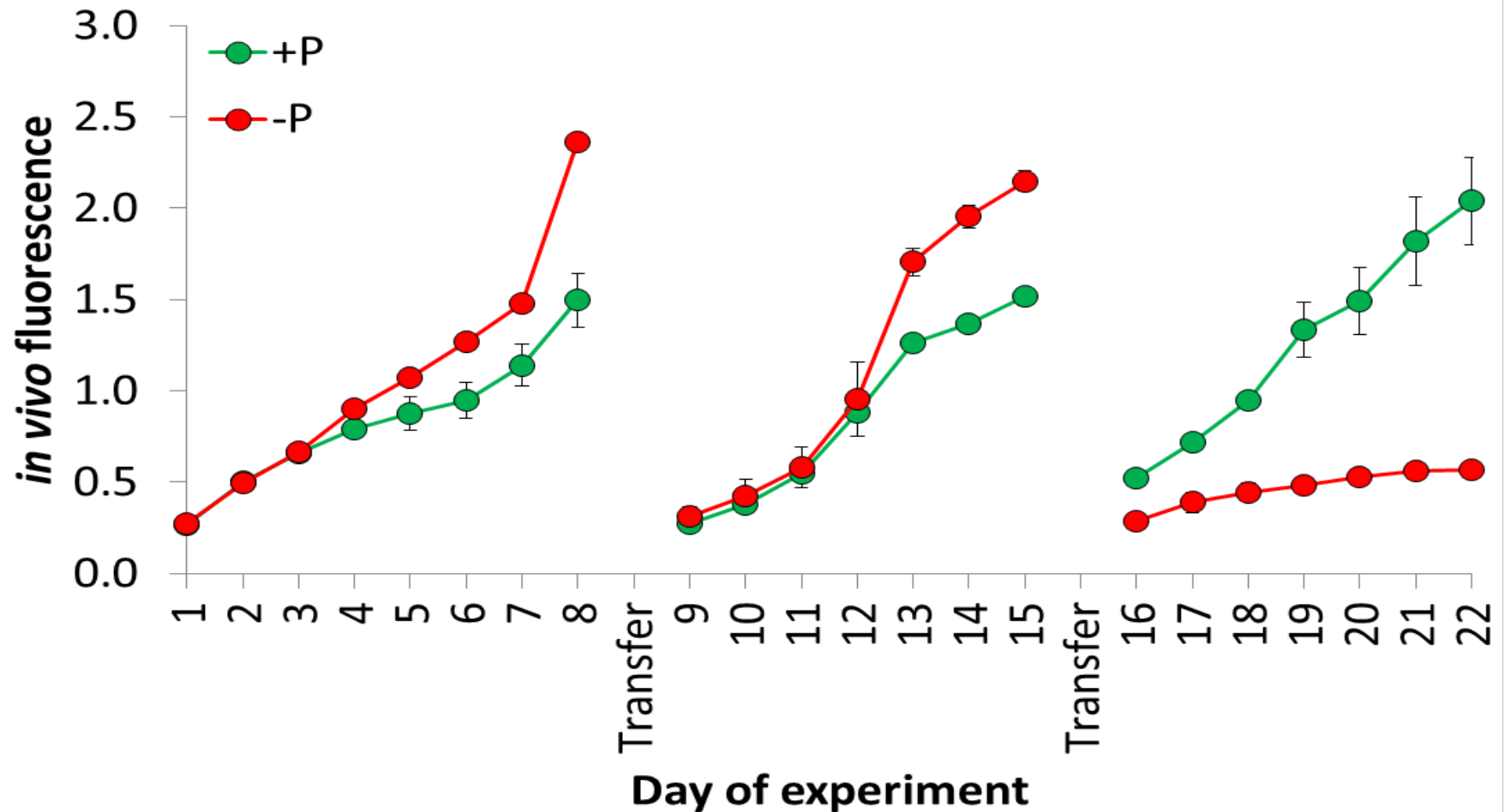
## Controlling Eutrophication by Reducing Both Nitrogen And Phosphorus

Daniel J. Conley,<sup>1\*</sup> Hans W. Paerl,<sup>2</sup> Robert W. Howarth,<sup>3</sup> Donald F. Boesch,<sup>4</sup> Sybil P. Seitzinger,<sup>5</sup> Karl E. Havens,<sup>6</sup> Christiane Lancelot,<sup>7</sup> Gene E. Likens<sup>8</sup>

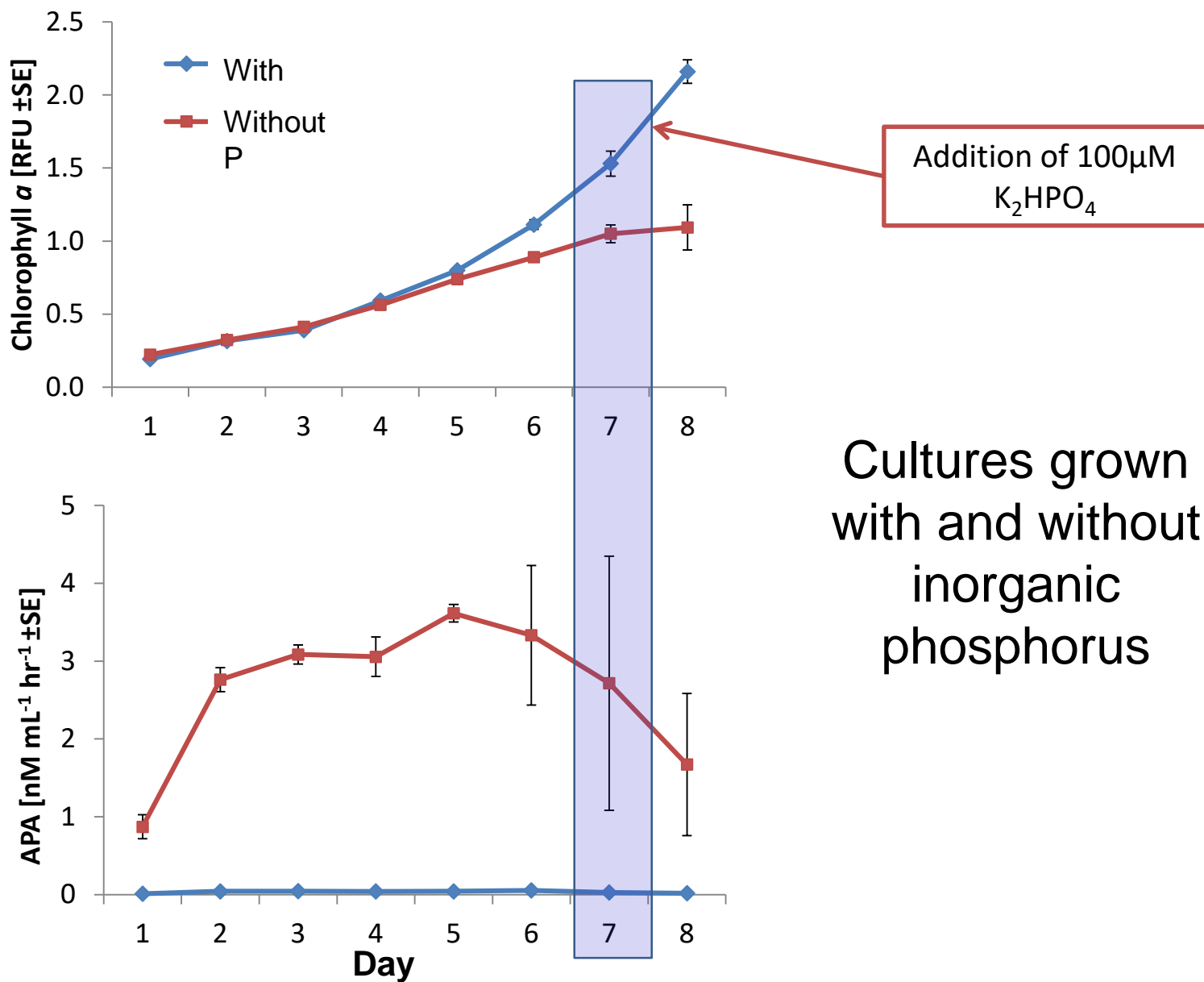
Improvements in the water quality of many freshwater and most coastal marine ecosystems requires reductions in both nitrogen and phosphorus inputs.



# Rapid growth of *Microcystis* without orthophosphate

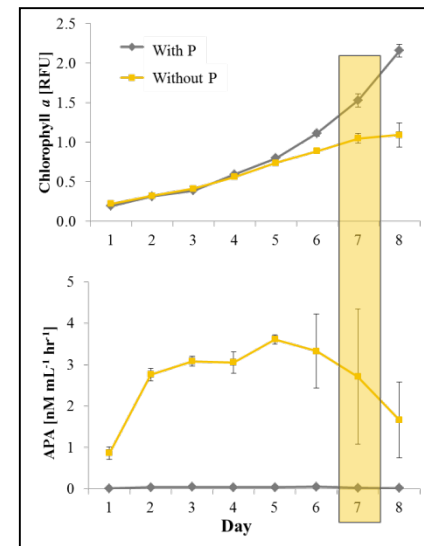
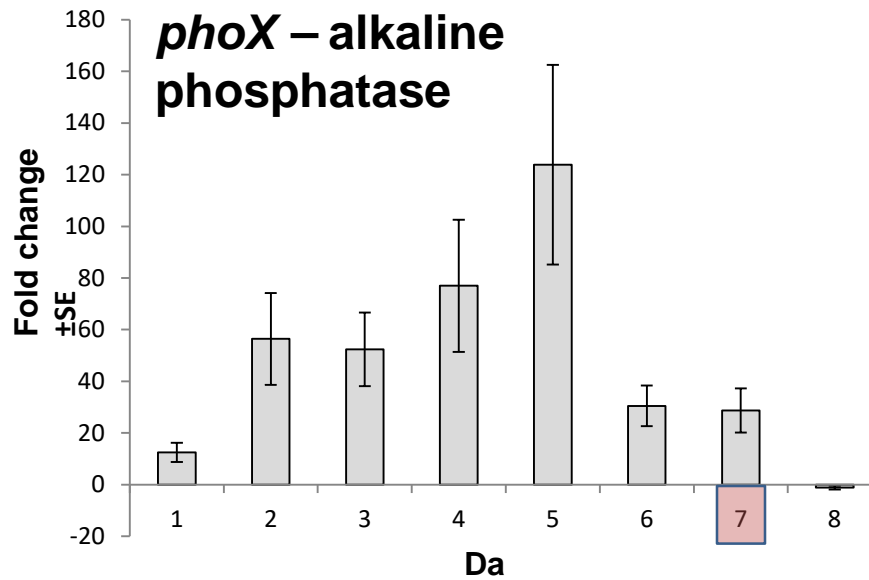



# Effects of P limitation on gene expression

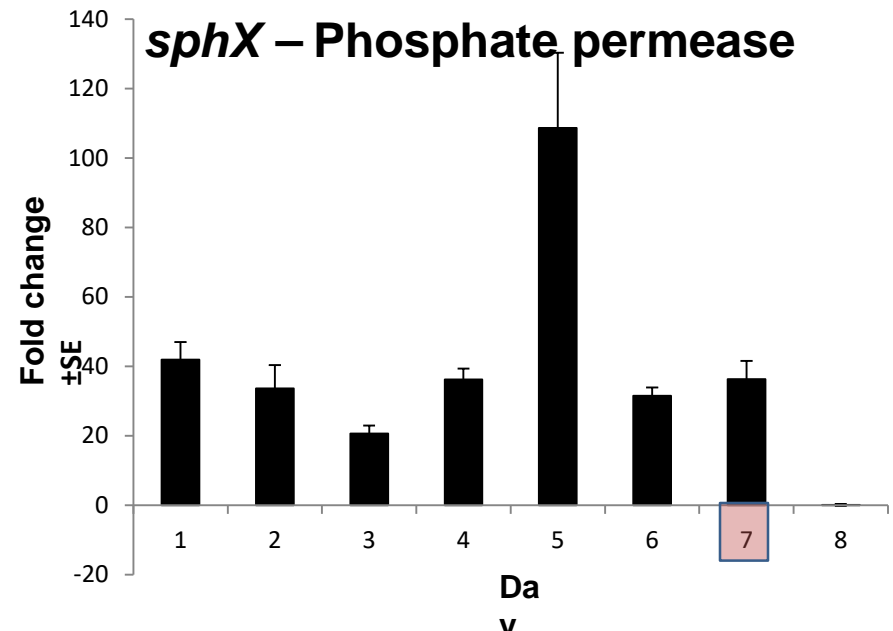
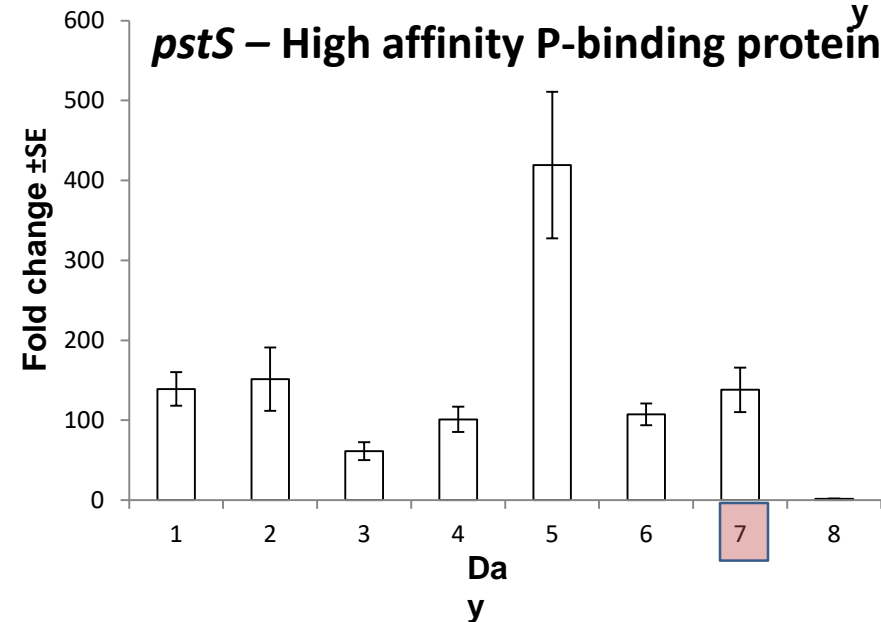


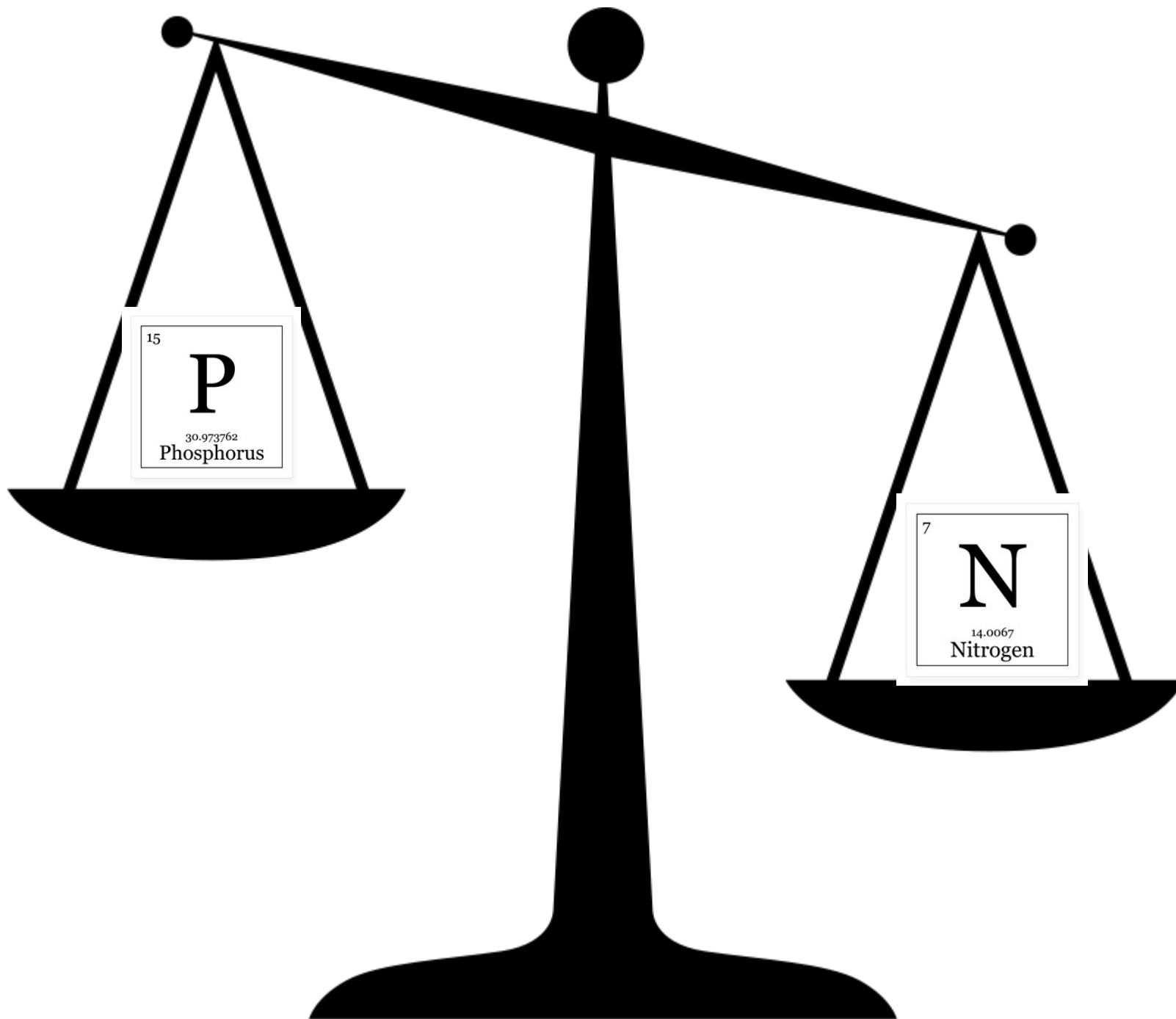


# Quantitative expression of target genes in P limited cultures relative to P-replete cultures

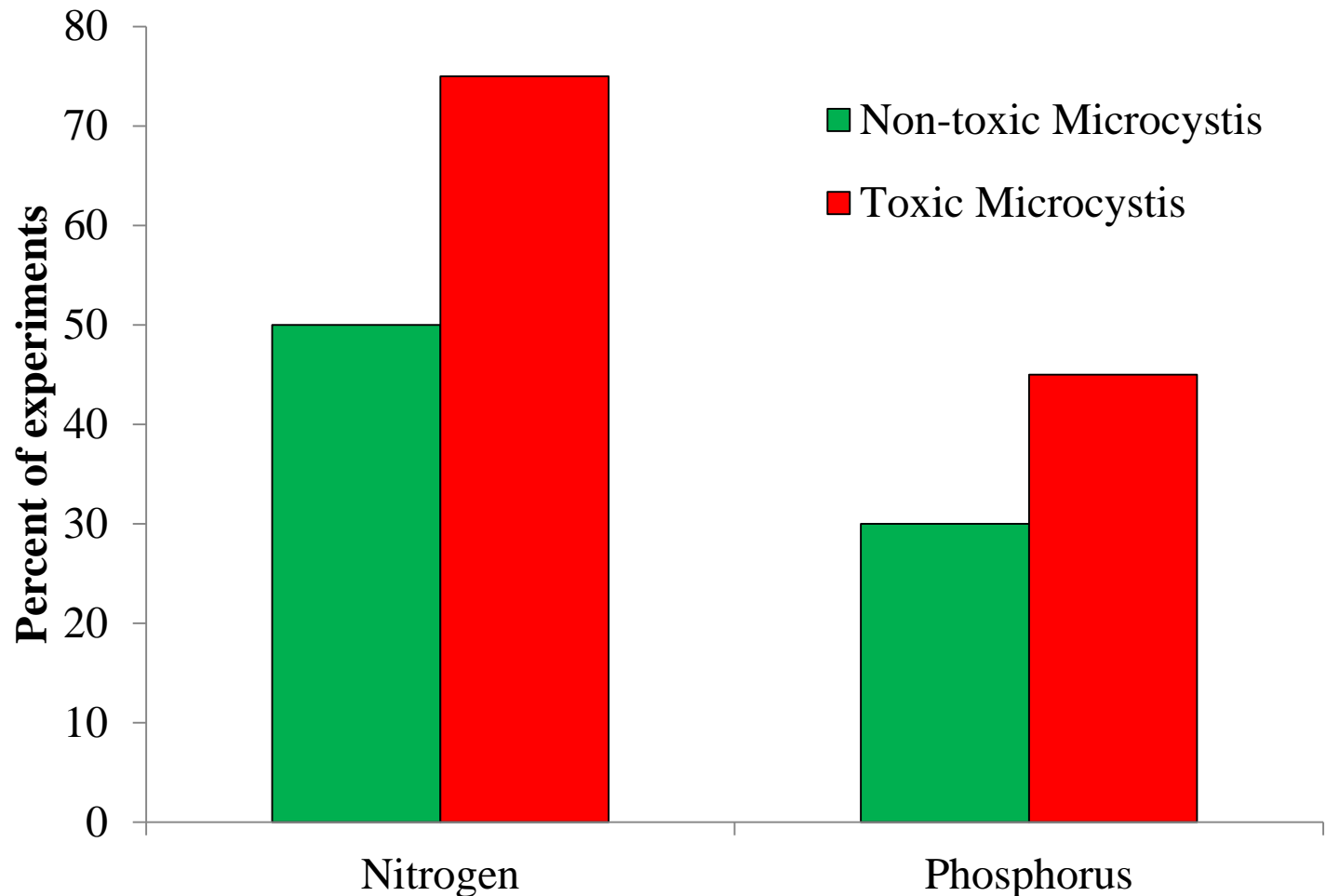


 = Addition of 100μM K<sub>2</sub>HPO<sub>4</sub>





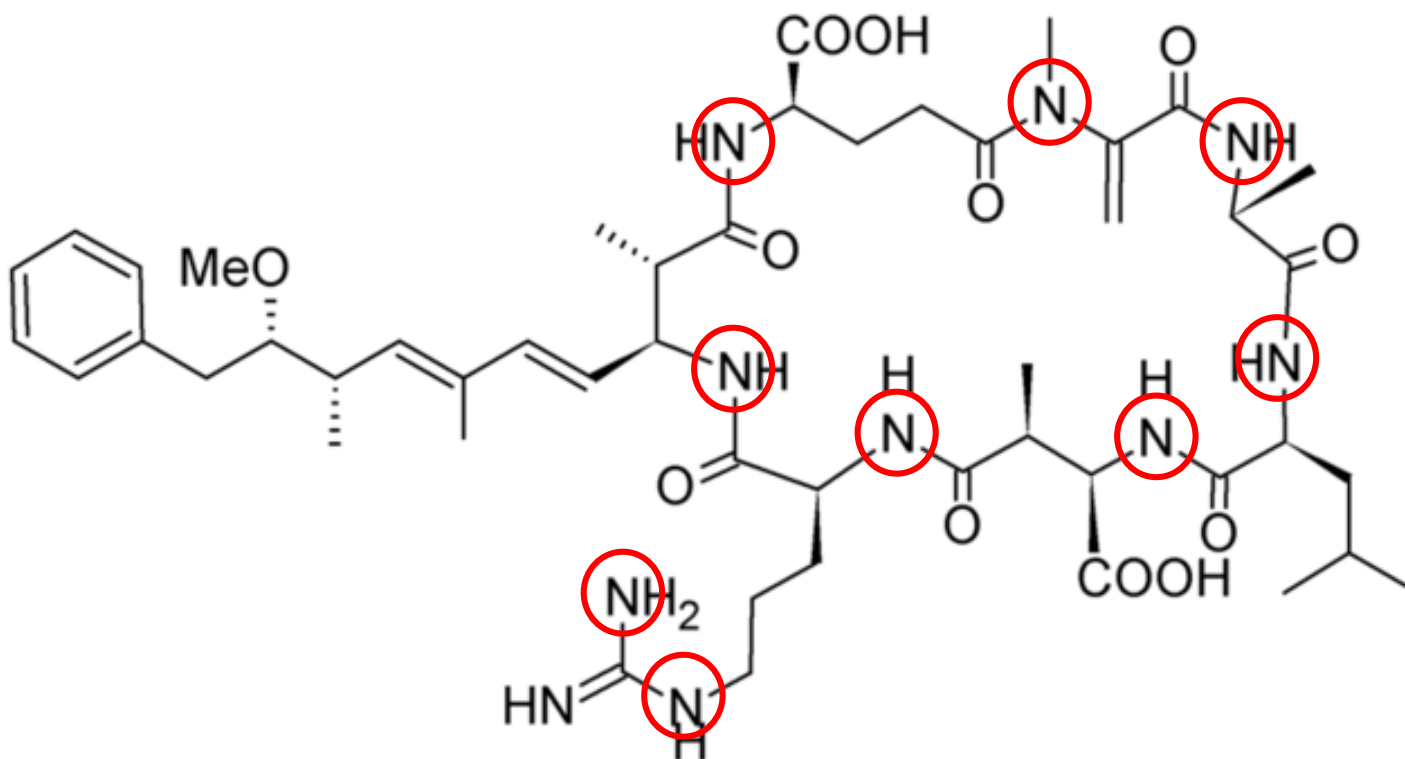
# Toxic strains of *Microcystis* were promoted by nutrients more frequently than non-toxic strains.



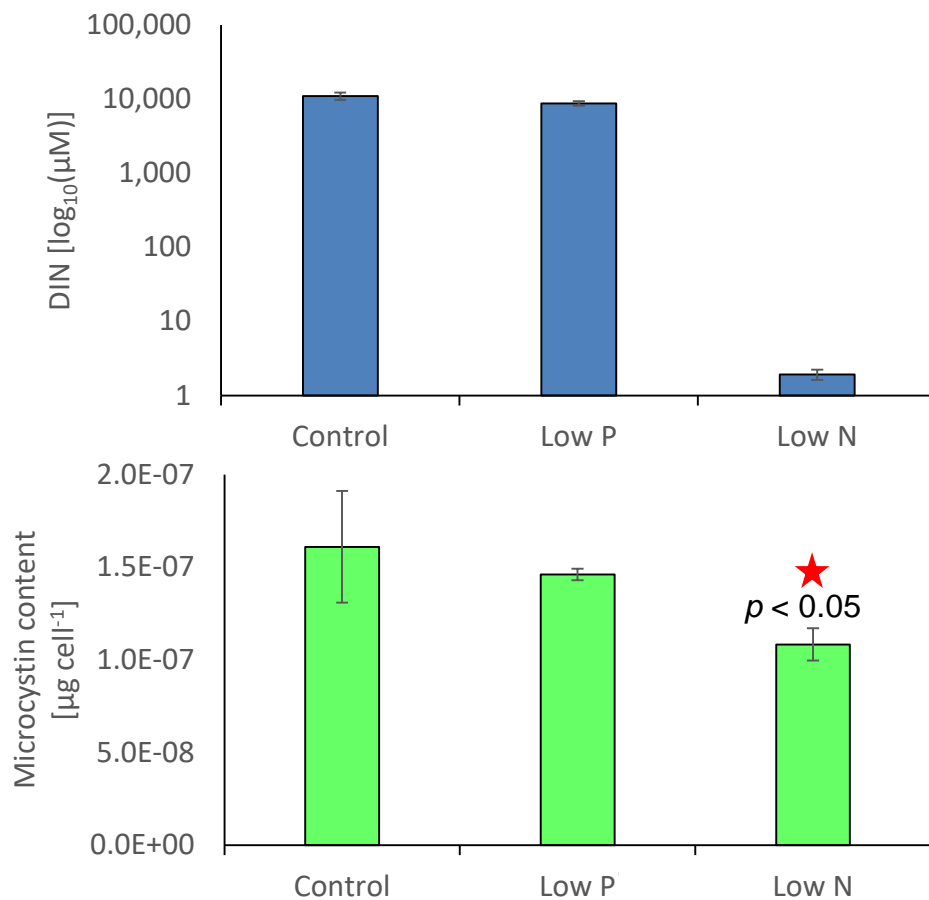
n = 12 experiments across two systems

Davis et al., 2010; Aquatic Microbial Ecology

# Linking nitrogen and microcystin

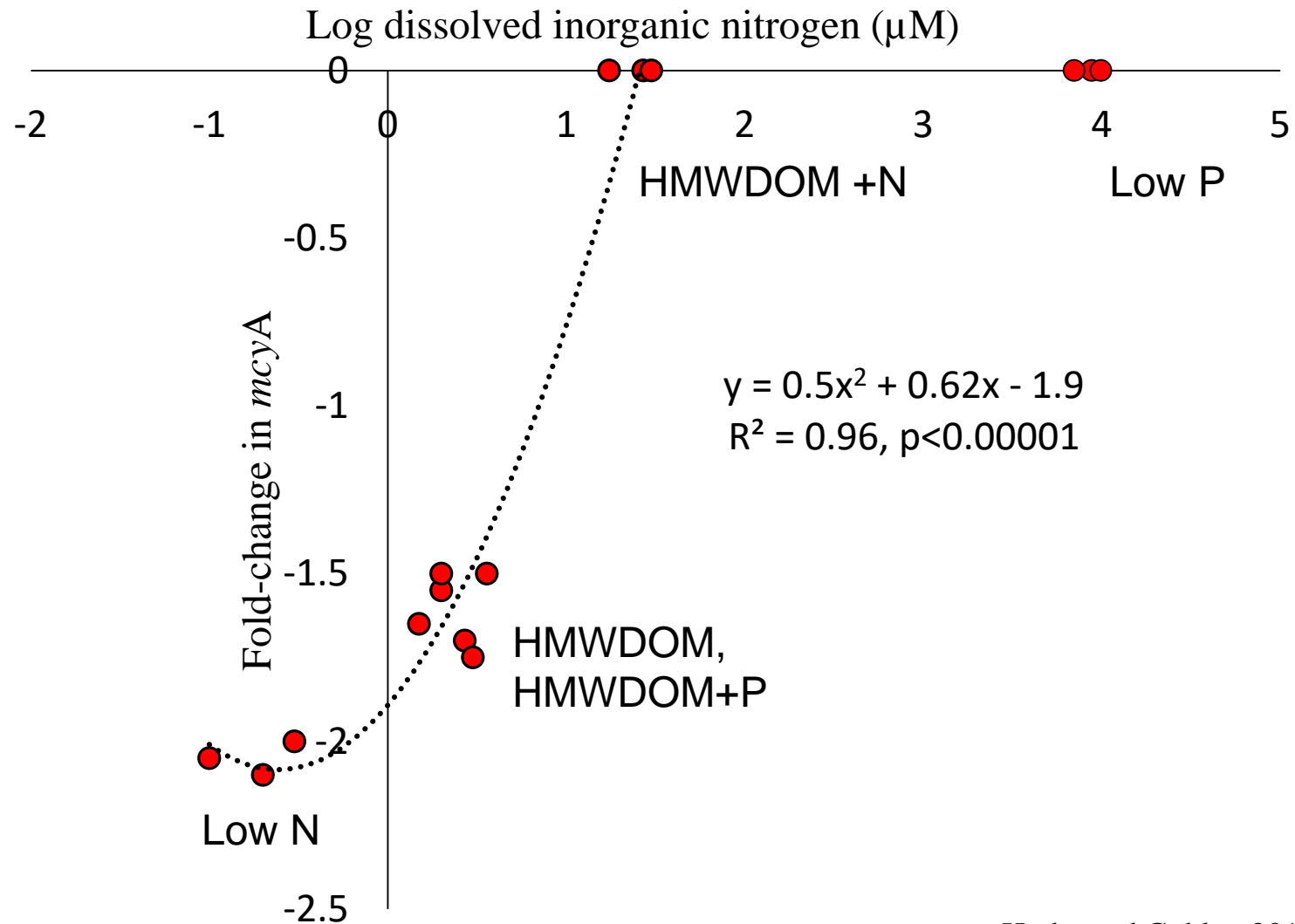


# The relationship between nitrogen supply and microcystin synthesis



- Significant reduction in microcystin quota under low N supply.

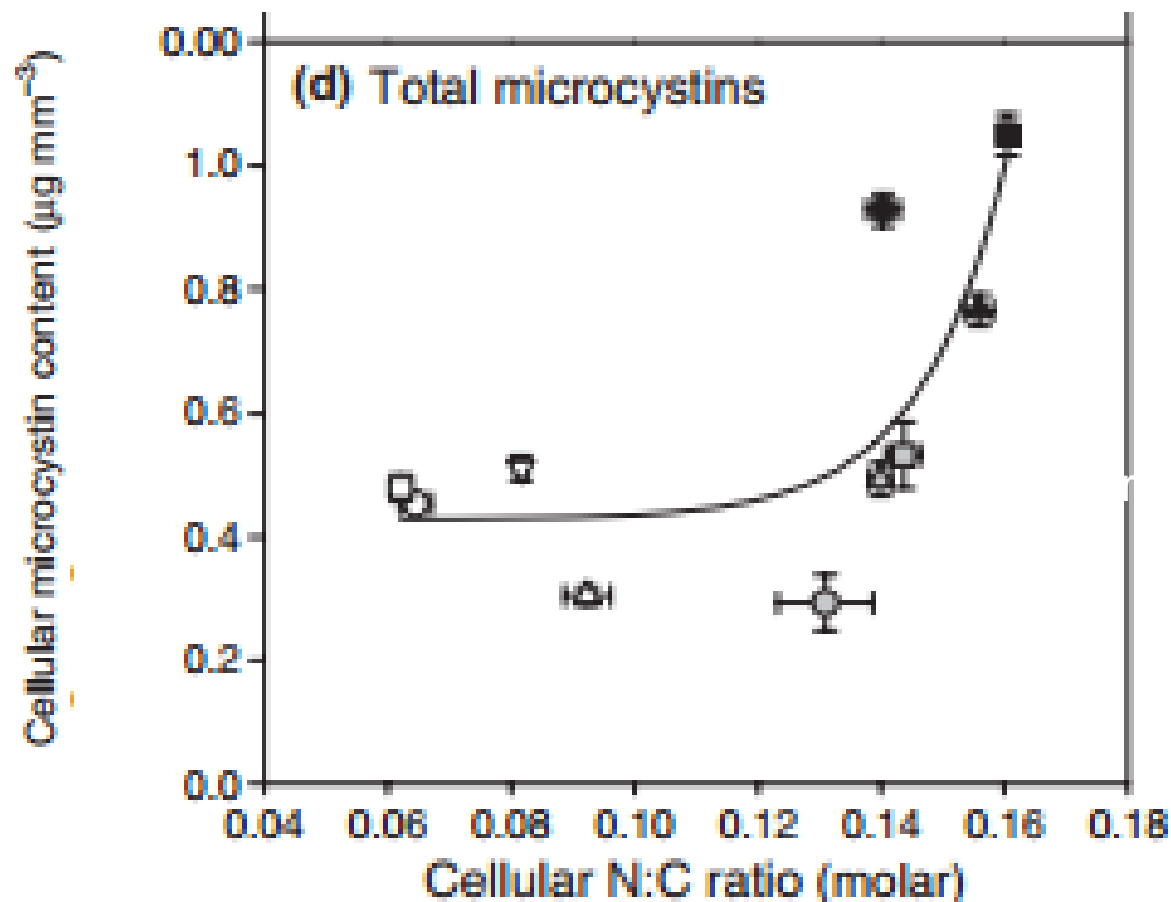
# Down-regulation of microcystin synthase under low nitrogen, all treatments





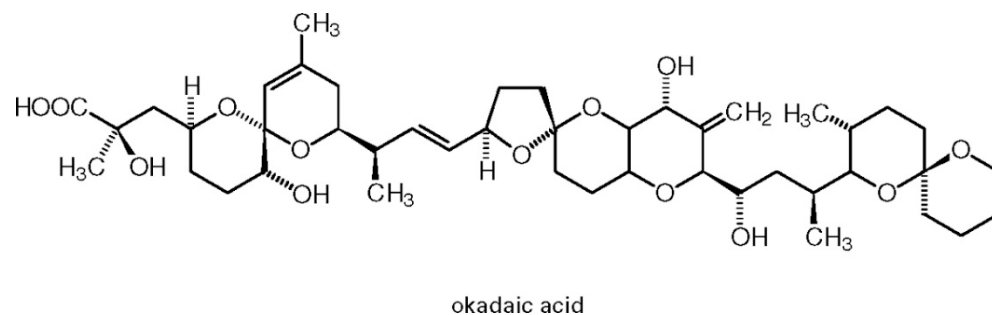
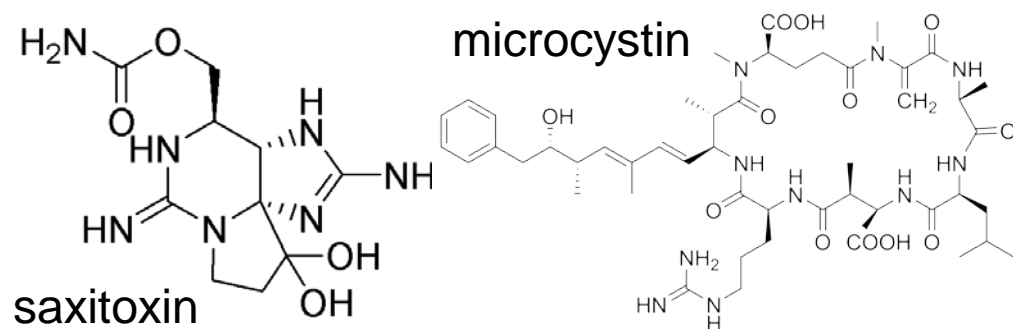
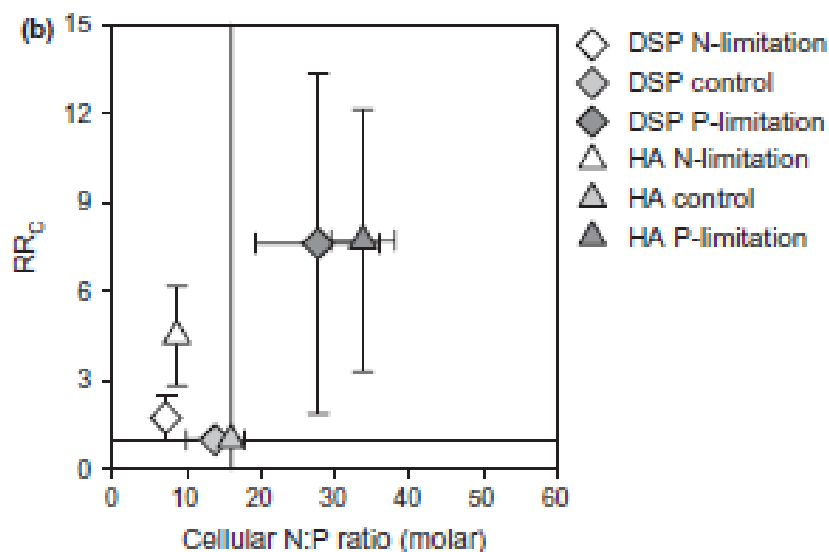
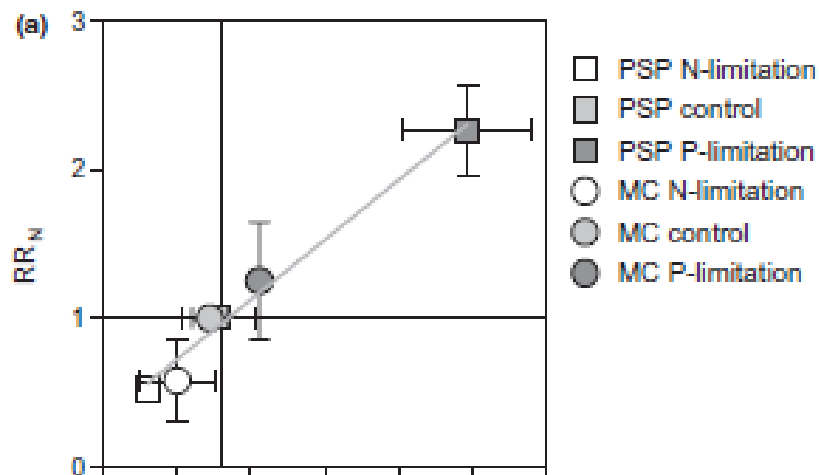
## LETTER

## Stoichiometric regulation of phytoplankton toxins



## LETTER

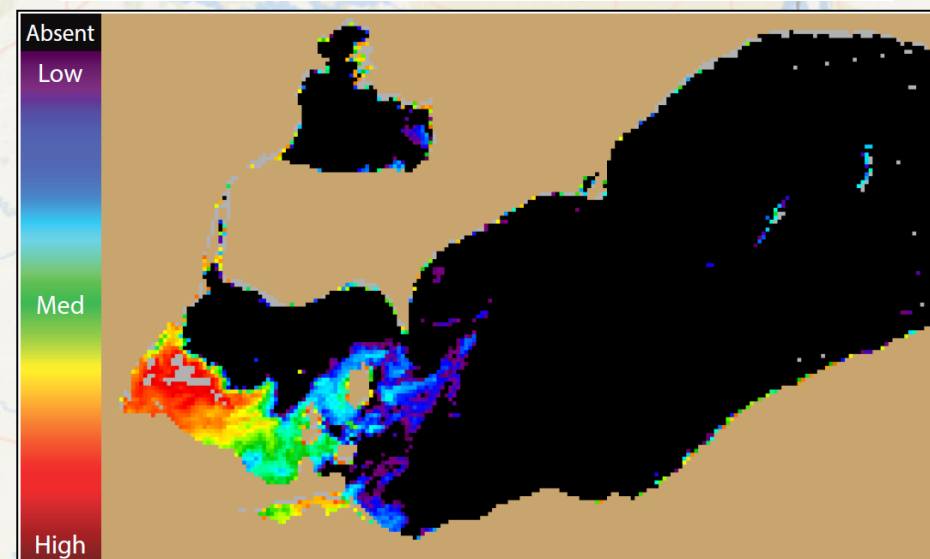
## Stoichiometric regulation of phytoplankton toxins



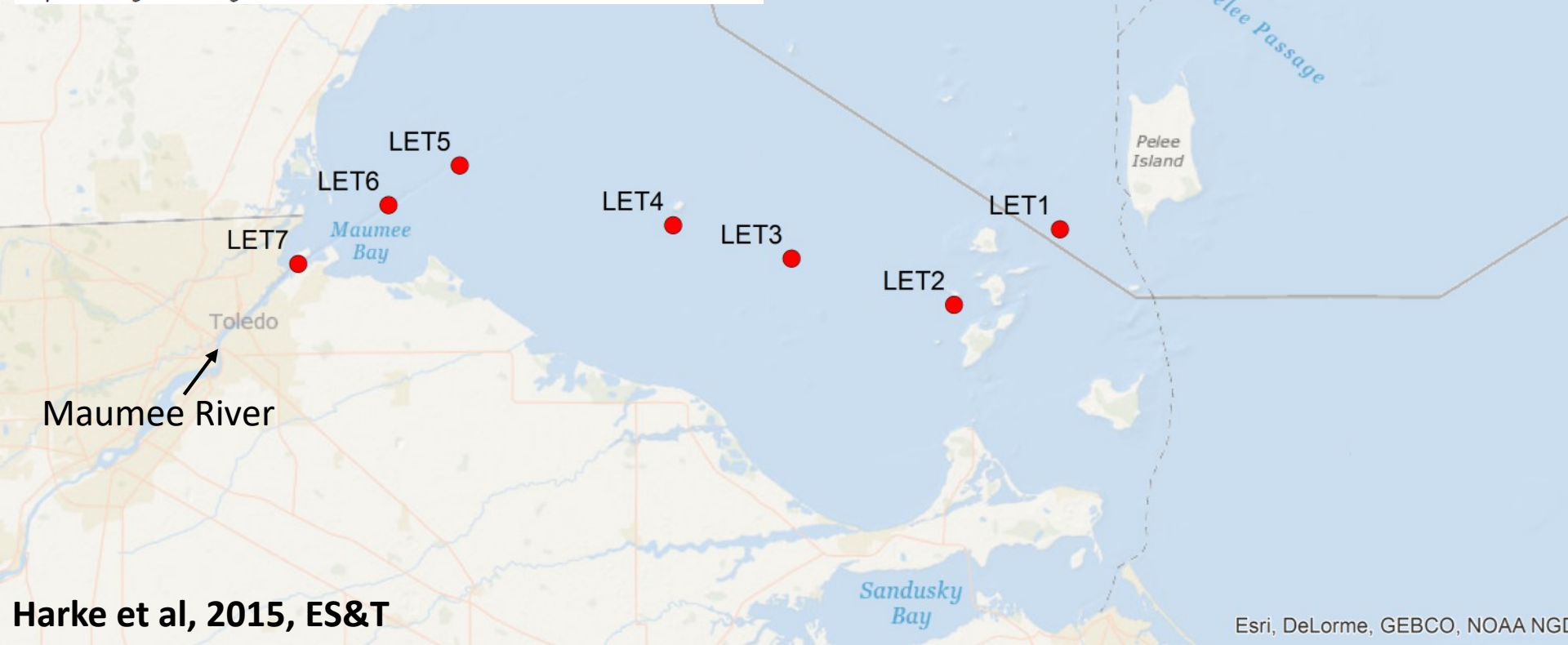
Nutrient-controlled niche  
differentiation among cyanobacterial  
populations across Lake Erie.



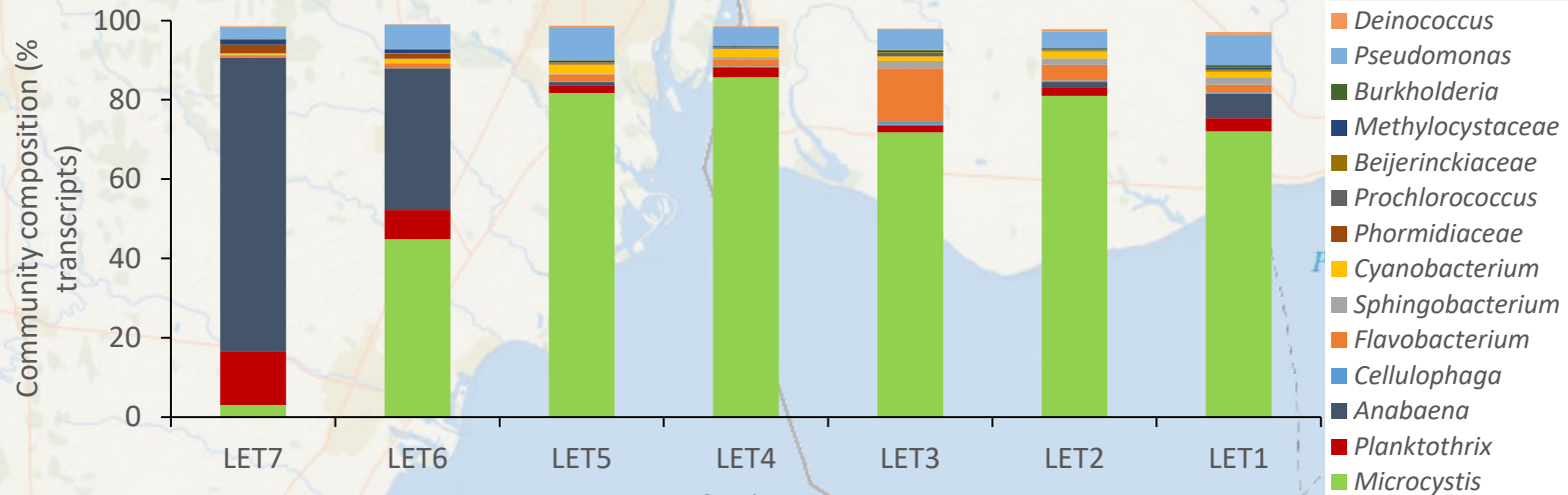
# Lake Erie transect, September 2013



[http://www.glerl.noaa.gov/res/Centers/HABS/lake\\_erie\\_hab/lake\\_erie\\_hab.html](http://www.glerl.noaa.gov/res/Centers/HABS/lake_erie_hab/lake_erie_hab.html)



# Lake Erie metatranscriptomes



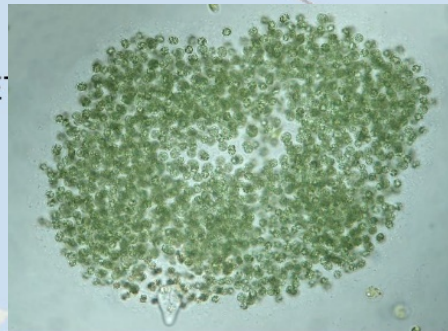
**Anabaena**

**Microcystis**



Anabaena

Maumee River



Microcystis

LET5

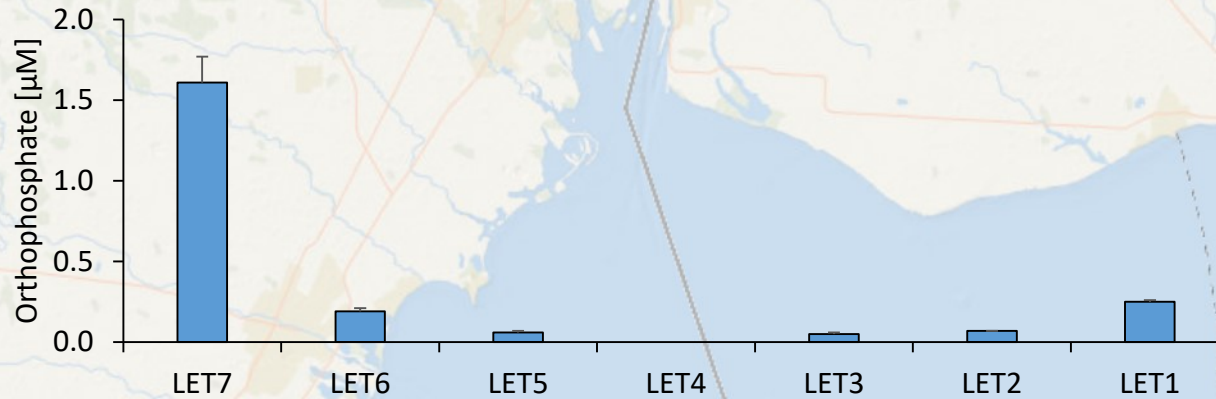
LET

LET1

Pellee Island

Sandusky Bay

# Orthophosphate and dominant cyanobacteria

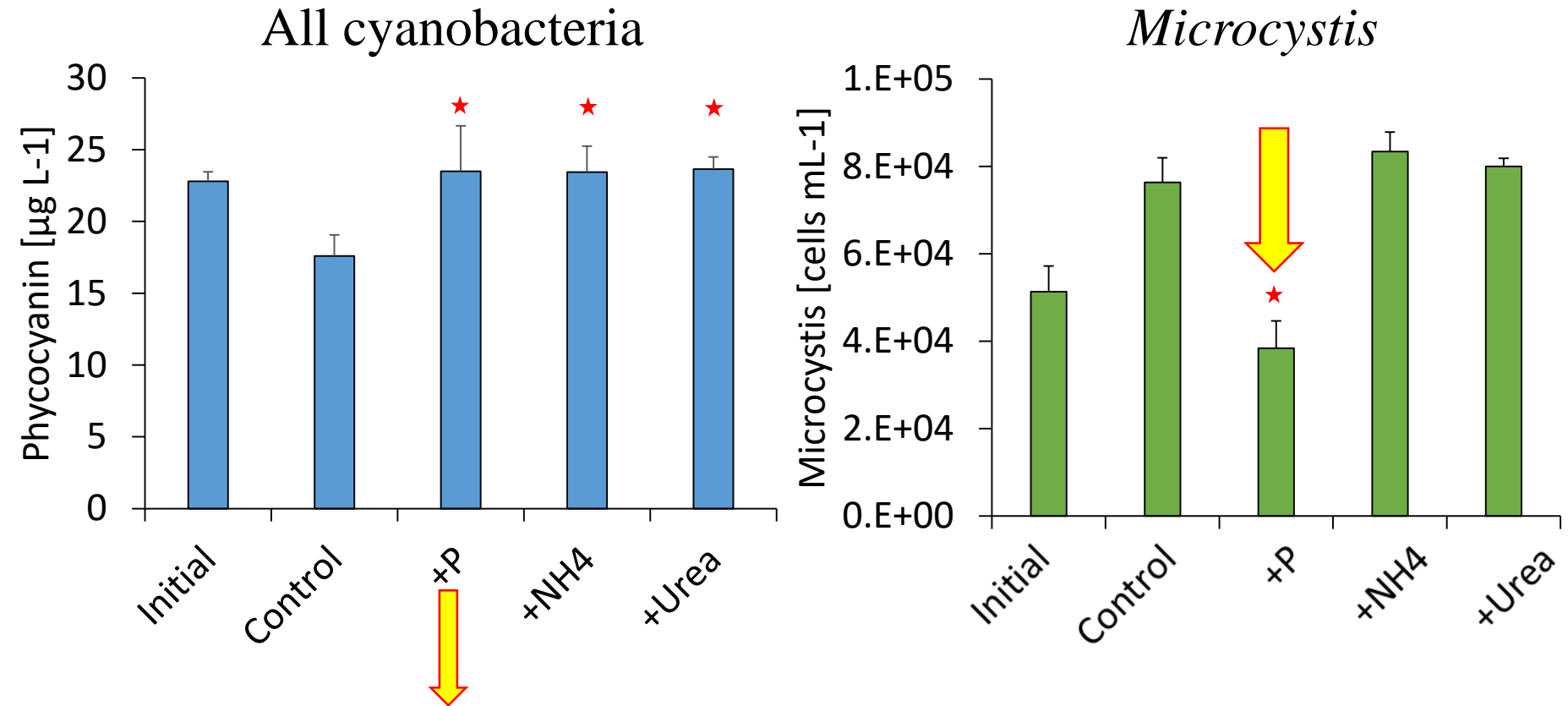


*Anabaena*

*Microcystis*

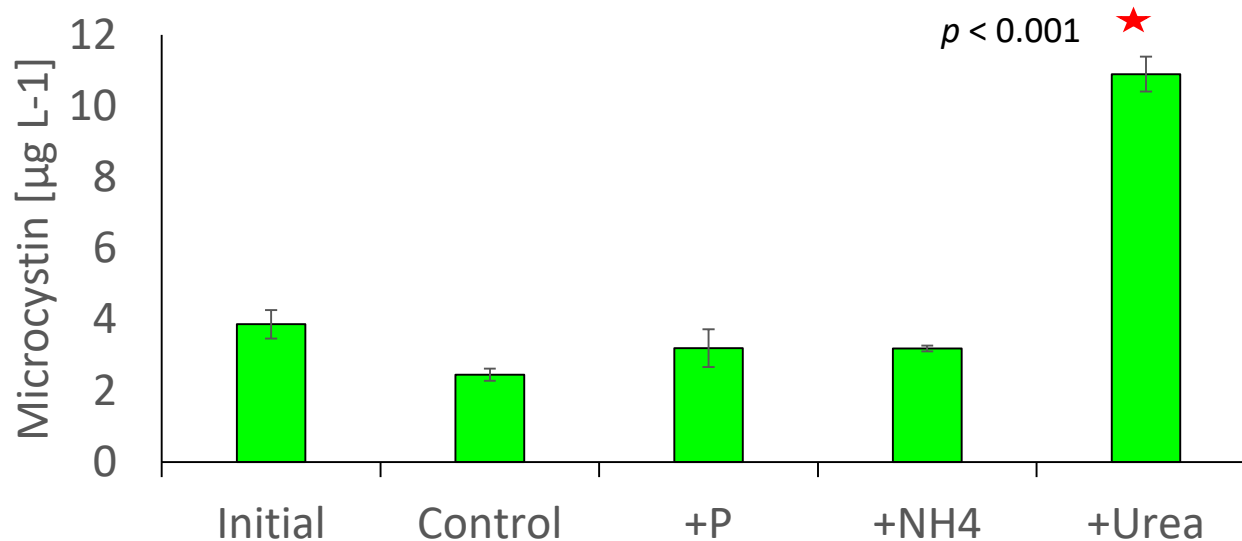


# Effects of nitrogen and phosphorus loading on cyanobacteria in Lake Erie

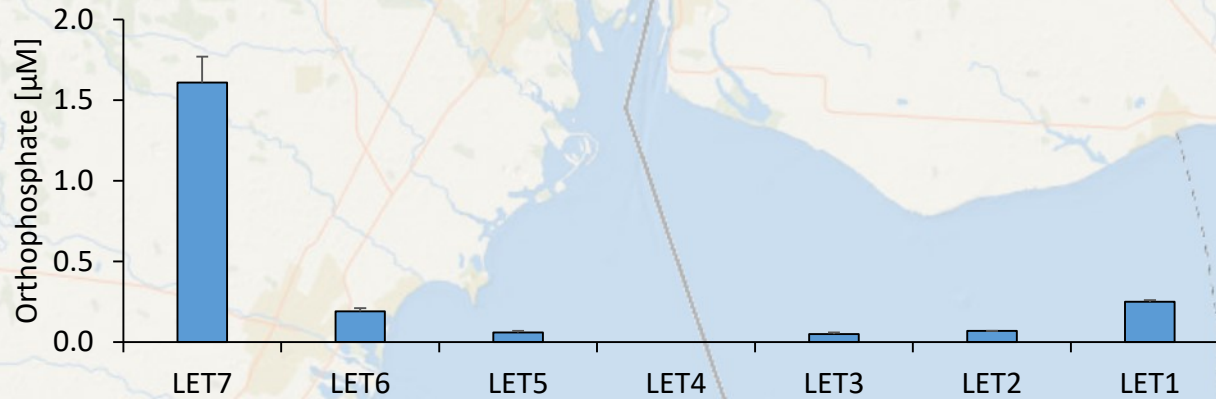


Up-regulates nitrogenase (*nifH*) in *Anabaena*.

# Incubation experiment: The relationship between nitrogen supply and microcystin synthesis



# Orthophosphate and dominant cyanobacteria

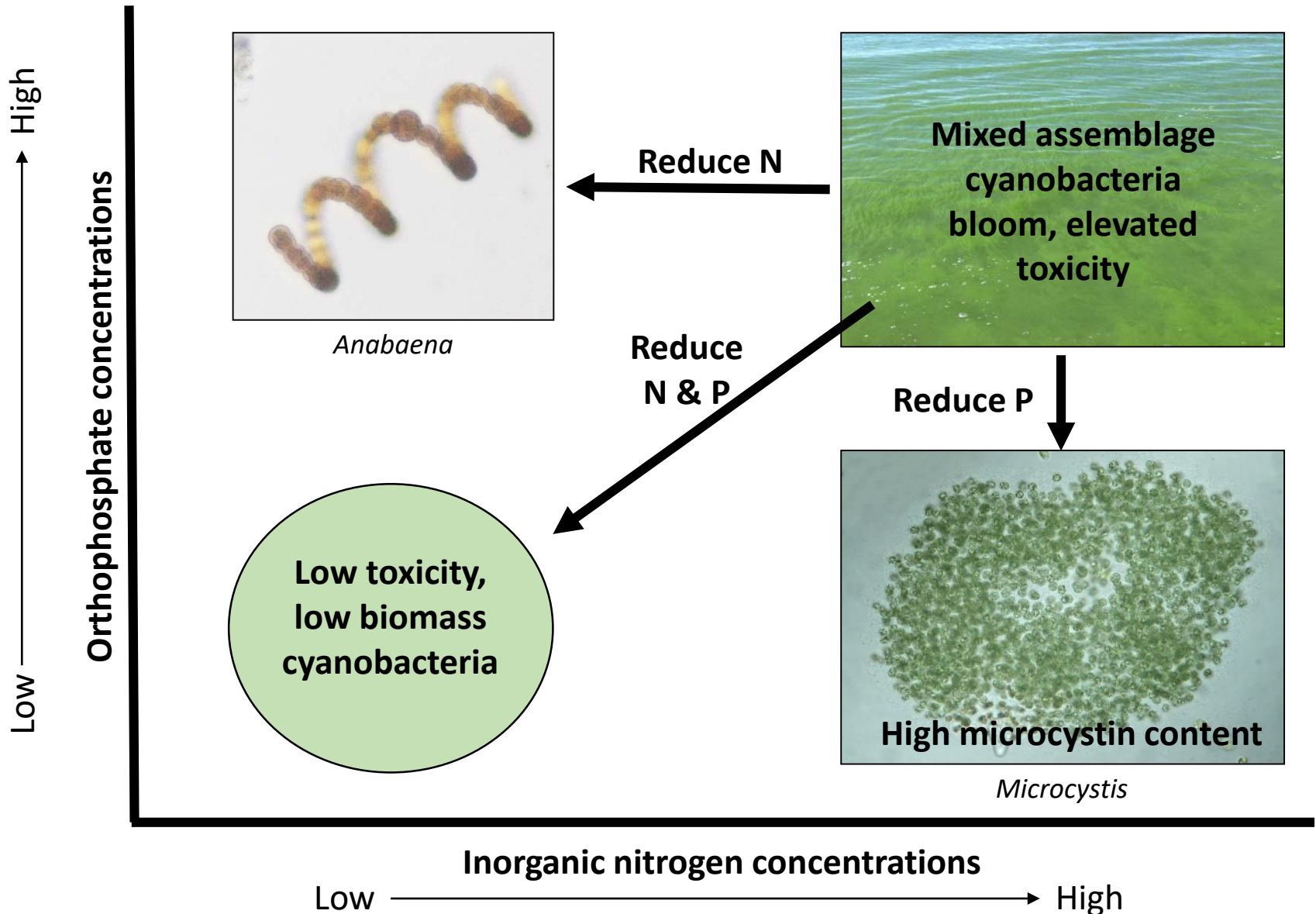


***Anabaena***

***Microcystis***



# Implications of reducing N and/or P





United States  
Environmental Protection  
Agency

Office of Water

EPA - 820-S-15-001

MC 4304T

February 2015

---

## *Preventing Eutrophication: Scientific Support for Dual Nutrient Criteria*

# *Are marine HABs always N-limited?*

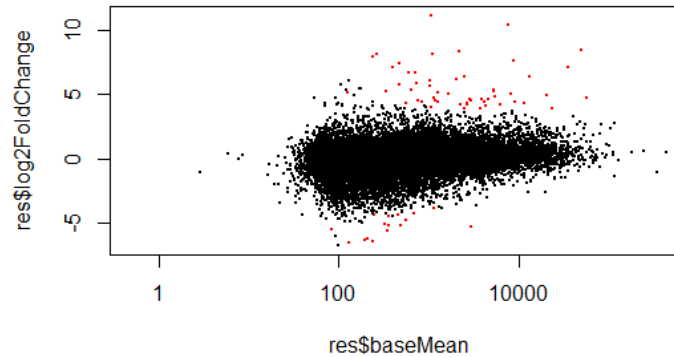
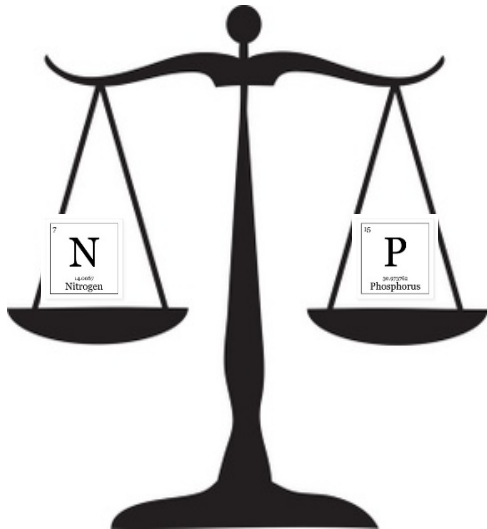


Brown tides caused by *Aureococcus*

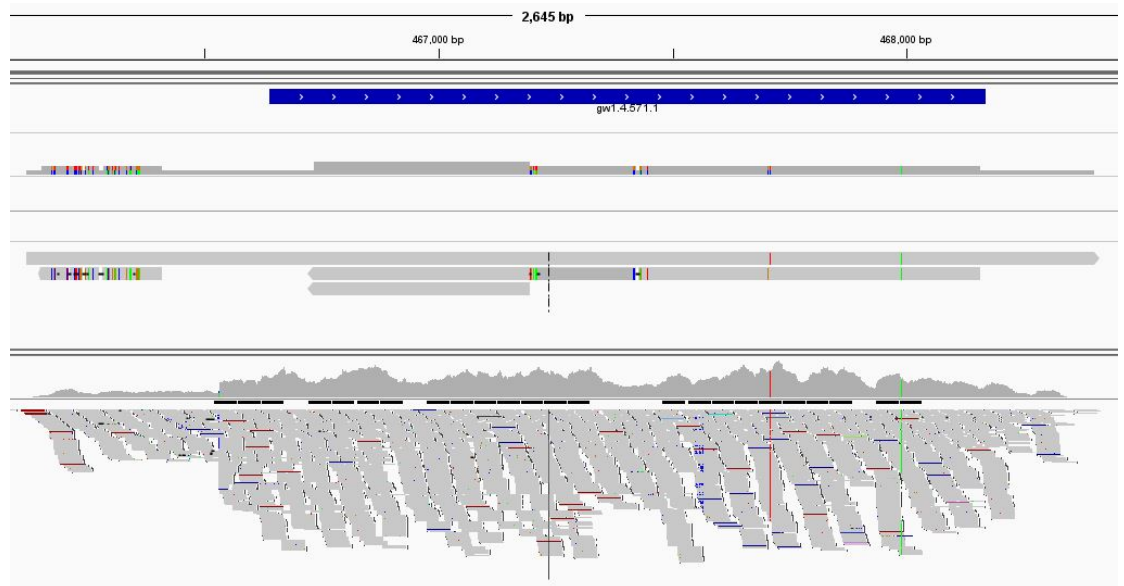
# ECOHAB: Resolving the Effects of Resource Availability, Predation and Competition on Brown Tide Dynamics Using Metatranscriptomics



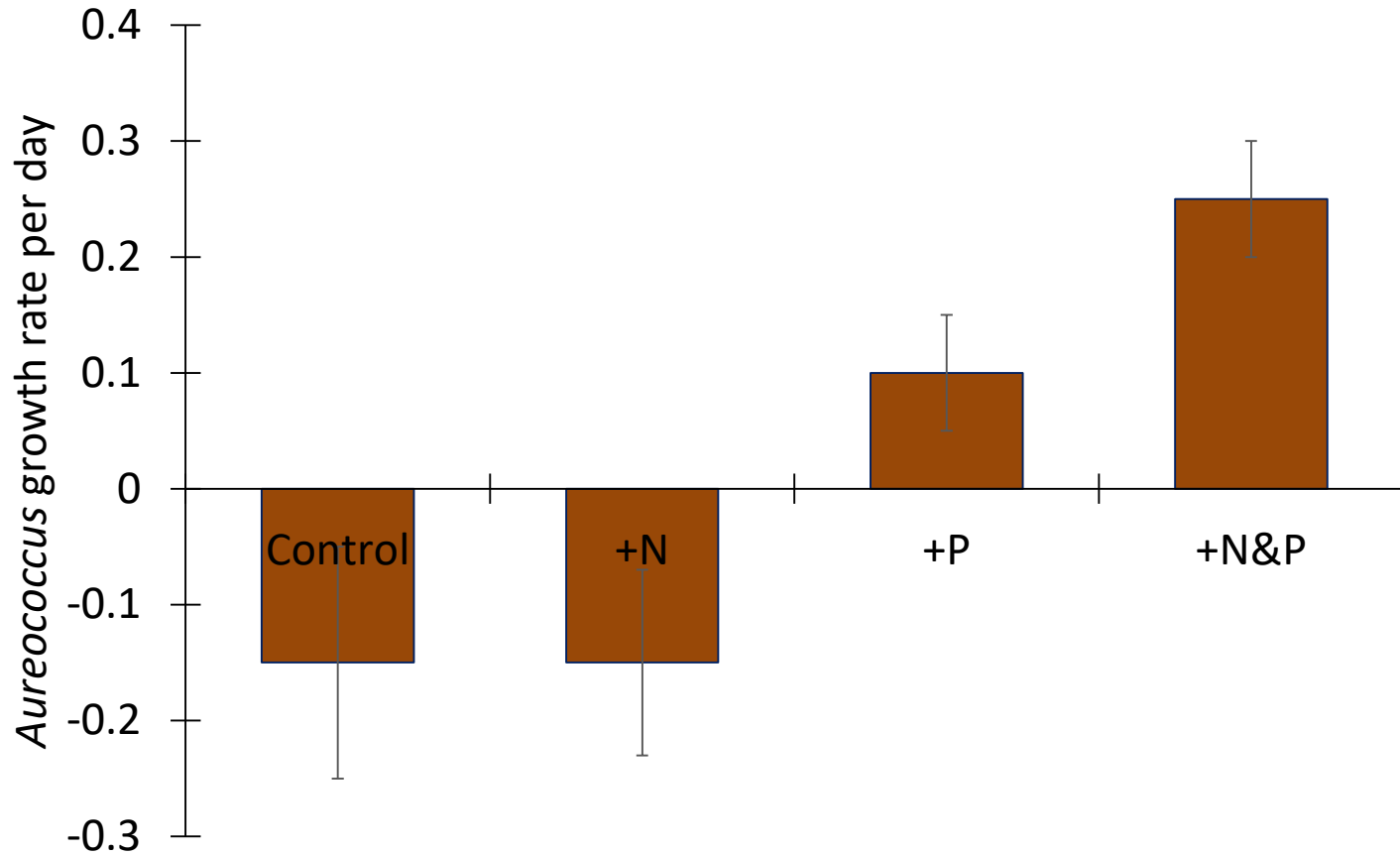
Sonya Dhyrman, Columbia Univ



©2012 Illumina, Inc. All rights reserved.

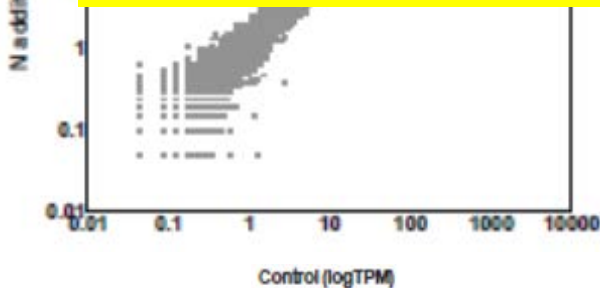


# Brown tide, Quantuck Bay, NY



# Nitrogen, phosphorus, brown tide

**Brown tides can transition from spring  
P-limitation to summer N-limitation**  
(Gobler et al 2002, 2004, 2005).



**Nitrogen  
addition,  
minor  
response**

# Conclusions

- There are multiple examples of HABs whose biomass AND toxicity are directly promoted by nutrient loading.
- Many important exceptions to this relationship exist: Some HABs thrive under low DIN.
- Nutrient ratios also influence HABs biomass *and toxicity*.
- Marine HABs can be P-limited; freshwater HABs can be N-limited.
- The extent to which HABs are controlled by nutrients must be assessed on a case-by-case basis: HAB-species and ecosystem-specific.